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Report of Pyrolysis of Sewage Sludges in the New York-New Jersey Metropolitan Area (Phase I)

Interstate Sanitation Commission, New York

Prepared for

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16. ABSTRACT

The purpose of this work was to reduce the volume of municipal wastewater (sewage) sludge in a multiple-hearth furnace via starved air combustion (pyrolysis) to determine how it compared with incineration as an environmentally acceptable method of sludge disposal. Sludge was first dewatered to 35-50 percent solids content in a plate and frame filter press having expandable rubber diaphram plates. The dewatered sludge was then thermally converted to ash and/or char in a .91 m (36 inch) inside diameter pilot scale multiple-hearth furnace having six hearths. Thermal conversion consisted of incineration at 900 °C (1625 °F) and starved air burning (pyrolysis) at 700 °C (1290 °F) to 900 °C (1625 °F). Heat contents of the off-gases and the ash and/or char mixtures were determined. The amounts of heavy metals retained in the ash and/or char were determined. Heavy metals retained by each mode of operation were compared to determine which process would cause the least air pollution. Toxic organics in the sludge were reduced below detectable limits in the ash and particulate emissions. This applied to all modes of operation. Particulate Emissions from starved air combustion (pyrolysis) were less than for incineration in most cases. A cost estimate for conversion of an existing plant to the starved air mode of operation is included in the report.

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PHASE I REPORT OF PYROLYSIS OF SEWAGE SLUDGES IN THE NEW YORK-NEW JERSEY METROPOLITAN AREA

by

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

The purpose of this work has been to develop a workable design for conversion of a plant scale multiple hearth municipal wastewater sludge incineration system to pyrolytic or limited air (oxygen) mode of operation. Ocean disposal of municipal sludge must be discontinued by 1981 and pyrolysis is being tested as a possible environmental acceptable and economical method of municipal wastewater sludge disposal.

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ABSTRACT

The purpose of this work was to reduce the volume of municipal wastewater (sewage) sludge in a multiple-hearth furnace via starved air combustion (pyrolysis) to determine how it compared with incineration as an environmentally acceptable method of sludge disposal.

Sludge was first dewatered to 35-50 percent solids content in a plate and frame filter press having expandable rubber diaphram plates. A polymer was added to the sludge as a filter aid prior to the filtration in most of the work.

The dewatered sludge was then thermally converted to ash and/or char in a .91 m (36 inch) inside diameter pilot scale multiple-hearth furnace having six hearths. Thermal conversion consisted of incineration at 900 ^{o}C (1625 ^{o}F) and starved air burning (pyrolysis) at 700 ^{o}C (1290 ^{o}F) to 900 ^{o}C (1625 ^{o}F).

Heat contents of the off-gases and the ash and/or char mixtures were determined. The amounts of heavy metals retained in the ash and/or char were determined. Heavy metals retained by each mode of operation were compared to determine which process would cause the least air pollution.

Toxic organics in the sludge were reduced below detectable limits in the ash and particulate emissions. This applied to all modes of operation.

Particulate Emissions from starved air combustion (pyrolysis) were less than for incineration in most cases.

Submicron size emissions appeared to increase as the temperature of operation increased.

A cost estimate for conversion of an existing plant to the starved air mode of operation is included in the report. The cost estimate includes installing a plate and frame filter system to replace an existing vacuum drum system.

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ABBREVIATIONS AND SYMBOLS

AB	Afterburner
ABD	Apparent bulk density
BDL	Below detectable limit
CBA	Carbon-burned ash; a pyrolysis product
$Cr+^3$	Trivalent chromium
$Cr+^6$	Hexavalent chromium
DS	Dissolved solids
DSCF	Dry standard cubic feet
EPA-5	EPA method 5 particulate loading measurement procedure (see gas sampling section of Appendix C for reference)
FF	Falling from, referring to hearth samples
GC	Gas chromatograph
HHV	Higher heating value (reference level is liquid water at 60°F or 18°C)
HTC	High temperature char pyrolysis product
HV	Heating value; all of the heating values in this report are higher heating values based on liquid water at 60°F
ISC	Interstate Sanitation Commission
Inc	Incineration
LDL	Lower detectable limit

LTC	Low temperature char pyrolysis product
Mg	Megagrams - Metric Tons
MHF	Multiple hearth furnace
NG	Natural gas
NYTL	New York Testing Labs
SCFM	Standard cubic feet per minute
SCFH	Standard cubic feet per hour
SS	Suspended solids
TS	Total solids

Steady State Nomenclature : Roman numerals refer to campaign number. The following letter (if any) refers to part A or B of the campaign. The first arabic numeral is the steady state number. The second number is the part of the steady state. "R" indicates a revised definition of the steady state.

Example: CIIA.2.1(R) is Campaign II Part A Steady State 2 Part 1 (Revised).

SECTION 1

INTRODUCTION

This report is part of a study funded by the United States Environmental Protection Agency (EPA)for the Interstate Sanitation Commission (ISC) concerning the disposal of sewage sludge in the New York-New Jersey metropolitan area. Specifically, this report covers the demonstration of sewage sludge pyrolysis in a pilot scale multiple hearth furnace as recommended by others. (1)

Approximately 400 hours of operation divided into three "campaigns" were conducted, coagulating, filter pressing and pyrolyzing raw sewage sludge from two plants and digested sludge from one plant. Information regarding air pollution, heavy metals distribution, solid product characteristics and heat recovery potential is used to determine design parameters. These parameters are applied in the form of a case study converting a typical multiple hearth incinerator to a pyrolyzer.

Pyrolysis is a chemical change in an organic substance reacting only with its own constituents, brought about by heating. Common examples are coking of coal and charcoal production from wood. Typically pyrolysis is carried out by indirectly heating the substance through a brick, steel or glass vessel wall to prevent air from reaching and reacting with the substance.

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(1) Phase 1 and Phase 2 Report of Technical Investigation of Alternatives for New York-New Jersey Metropolitan Area Sewage Sludge Disposal Management Program, June 1976

Prepared for Interstate Sanitation Commission, New York, New Jersey, Connecticut

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It is conceived that in thermal destruction of sludge by pyrolysis in a multiple hearth furnace solids are spilled along the floor of compartments while a large vapor space exists above the solids. When limited amounts of air are properly introduced into the vapor space, the oxygen reacts with the organic vapors present and there is starved air combustion (not pyrolysis) of those vapors.

However, the oxygen does not, in the proposed designs, persist through the vapor space and reach the solids. The solids do not react with oxygen. They receive heat by radiation from the vapor space, the sidewalls, the brick arch forming the top of the chamber, and by conduction from the chamber below. They are shielded from contact with the oxygen by a stagnant film of organic vapor or water or both leaving the stirred bed of solids. Adding to the protection is the fact that the limited amount of air admitted has its oxygen consumed rapidly in the organics rich vapor phase. This is pyrolysis with respect to the solids.

SECTION 2

SUMMARY

GENERAL

The primary objective of demonstrating sewage sludge pyrolysis in a pilot plant scale multiple hearth furnace was accomplished. It was also demonstrated that pyrolysis can be used as a thermal destruction method for sludge disposal without using fuel.

Pyrolysis of representative sewage sludges from the New York - New Jersey metropolitan area was successful. In general it is concluded that thermal destruction of sewage sludge by pyrolysis is a commercially feasible and cost effective process.

PYROLYSIS

Design parameters for the pyrolysis process are presented such as, furnace capacity, heating value of product gas, fuel requirements at varied modes of operation, and solid product properties. It is shown that pyrolysis process parameters with respect to the incineration process are as follows:

Solid Products--Depending on mode of pyrolysis operation, there are three types of product that can be produced, i.e., low temperature char (LTC) that allows maximum heavy metals retention, high temperature char (HTC) that allows maximum throughput and carbon burned ash (CBA) that allows maximum heat recovery. The latter is equivalent to the solid product produced by incineration.

Capacity--in a fixed size furnace pyrolysis allows a greater throughput rate.

Heating Value of Product Gas--under autogenous conditions pyrolysis CBA allows greater overall heat recovery.

Fuel Requirements--Pyrolysis has significant fuel savings.

ENVIRONMENTAL ASSESSMENT

Particulate losses with respect to total particulate and heavy metals content of particulate were studied. In general, total particulate losses during pyrolysis operation were less than those of corresponding incinerations.

Volatilization of heavy metals is dependent on the furnace operating temperature. As stated above, LTC (lowest operating temperature) retains most of the heavy metals in the solid product. Cadmium and mercury are problematic in that they have the highest volatility of the metals investigated (Cu,Cr, Ni, Zn, Pb, As, Cd, Hg). Feed and product chromium analysis showed that neither incineration nor pyrolysis increased the soluble, Cr^{+6}, form of chromium.

FEED PREPARATION

Eight representative sewage sludges were investigated and seven of these were successfully dewatered by filter pressing. Typical sludge cakes produced were 30 to 45% dry solids. Three of the seven sludges were chosen for the pyrolysis study covered by this report. Detailed analysis of these 3 sludges were made with respect to solids, toxic organics, combustibles, heating value of solids, heavy metals and ash content.

ECONOMICS

An estimate of the cost of converting an existing incineration system (22'3" O.D. by 10 hearths) to pyrolysis is presented. It was estimated at $400,000, including construction of the required afterburner. To add an afterburner to an existing incinerator system is estimated to cost $200,000.

Converting from incineration to pyrolysis yields substantial fuel savings. These fuel savings yield a 2½ to 4 year payout on the added capital investment for conversion.

SECTION 3

CONCLUSIONS

1. Experimental results clearly show that pyrolysis of sewage sludge is readily accomplished in the multiple hearth furnace. Autogenous operation was demonstrated, including afterburning above 1400 ^{o}F (760 ^{o}C).

   Split drafting was demonstrated to be the preferred technique to control pyrolyzer operation. Although the pilot furnace had no automatic controls this technique would lend itself well to them. This technique provided an even temperature distribution throughout the furnace along with control of the furnace temperature.

2. Furnace capacity varies with mode of pyrolysis. For vacuum filter systems (22% dry solids); the highest capacity is obtained when producing high temperature char (HTC); 15 wet lbs./(hr-ft^2) (78 kg/hr-m^2). When low temperature char (LTC) is produced, the feed rate can be 13 wet lbs/(hr-ft^2) (64 kg/hr-m^2). If complete consumption of the carbon is to be accomplished, the feed rate becomes 12 wet lbs./(hr-ft^2) (59 kg/hr-m^2).

   For filter press cakes of 35% dry solids the wet feed rates do not change significantly from those above. However, it should be noted that more dry solids are handled per unit area.

   These are maximum rates and appropriate reductions need be considered in design to allow for anticipated variations in feed rate and composition.

3. The off-gas heating value varies with the feed heating value and moisture content. For the sludges and operating ranges tested the off-gas net heating values ranged from 18.4 to 73 BTU/SCF (690,000 to 2,700,000 J/SCM.)

4. For a given plant having a filter pressed feed of 32% dry solids, the MHF operating in an LTC or HTC mode and required to afterburn at 1400 ^{o}F, 15% excess air, the fuel savings for pyrolysis as compared to incineration is 50% (20 gal/dry ton for pyrolysis vs. 40 gal/dry ton for incineration, i.e. No. 2 fuel oil). At similar conditions, but in a pyrolysis, CBA, mode no fuel would be required, whereas incineration would still demand 40 gal/dry ton of fuel oil.

5. The fuel savings resulting from conversion to pyrolysis will repay the investment in 2½ to 4 years.

6. Some specific reasons for selecting among the modes of pyrolysis:

   LTC-Heavy metals retention
   HTC-Maximum furnace throughput
   CBA-Maximum heat recovery

7. Pyrolysis char bulk densitities ranged from 16 lbs/ft^3 (.26 g/cm^3) at 75% ash to 33 lbs/ft^3 (.53 g/cm^3) at 97.5% ash.

8. Heavy metals retention is related to maximum solids temperature. Drastic losses of Pb and Zn occur above 1500 ^{o}F (820 ^{o}C). Less than 7% Hg retention is observed even at the lower temperatures, and in nearly all cases it is below 1%. Cd retention dropped from 45-70% below 1200 ^{o}F (650 ^{o}C) to about 25% at higher temperatures. The metals examined can be classified into three groups:

LOW VOLATILE	VOLATILE	HIGHLY VOLATILE
Cu	Zn	Cd
Cr^{+3}	Pb	Hg
Ni	As (?)	

9. In most cases particulate losses during pyrolysis operation were less than those of corresponding incinerations. In 3 out of 6 cases pyrolysis with afterburning and without scrubbing met the EPA sewage treatment plant incinerators particulate limit of 1.3 lbs. ton of dry sludge.

10. Indications are that the quantity of submicron particles is related to the maximum bed temperature. Further study is recommended.

11. During filtration the toxic organics (pp'DDE, Dieldrin, PCB) are contained in the solid cake. Both incineration and all modes of pyrolysis were successful in removing these from the solids. However, total destruction cannot be confirmed because the maximum possible stack gas concentration (for sludges tested) remained below the detectable limits.

12. Seven of the eight sludges testing during preliminary evaluations were successfully filter pressed. Filter cakes were successfully filter pressed. Filter cakes produced were between 30 and 45% dry solids.

    Three sludges were chosen for the pyrolysis demonstrations. Equivalent filtration results were produced on a commercial scale filter press.

13. For Camapigns II and III expandable diaphragm plates were used in the commercial sized press. This allowed shortening the cycle by 50% or more.

SECTION 4

EXPERIMENTAL CHRONOLOGY

Chronologically the work can be separated into three tasks 1) preliminary filter press studies, 2) furnace operation and 3) some short follow-up experiments.

Preliminary filtration studies began in September, 1976. These studies resulted in the selection of Coney Island, N.Y. digester product and feed and Rahway, N. J. raw sludges for subsequent furnace pyrolysis campaigns.

Campaign I was conducted on November 15-19, 1976. The furnace feed was Coney Island, N. Y. digested sewage sludge. Most of the feed was polymer-conditioned and filter pressed, but ferric chloride-lime conditioning was also tested. No cake breaker was used and the polymer conditioned filter cakes resulted in wet lumps in the furnace product.

Campaign II was in two parts; the first part (part A) was on January 4, 1977 and the second part (part B) was on February 21-25, 1977. Polymer-conditioned Coney Island, N. Y. raw sludge was filtered for furnace feed. A blade comminutor chopped the feed into small enough pieces that no lumps appeared in the furnace product. Sub-zero weather interrupted the first week's test. That test was notable in that, due to the natural gas shortage, autogenous operation of the furnace and afterburner was mandatory. During the second half the Campaign II schedule was completed and an incineration run was performed. Split-drafting of the furnace was also demonstrated as the preferred method of control.

Campaign III was run on June 21-25, 1977. The feed was filtered from polymer-conditioned Rahway, N. J. raw sludge. This sludge produced a somewhat wetter filter cake than Coney Island, N. Y. raw sludge, but it had a higher heating value, making it nearly as easy to pyrolyze. A pair of rotating rollers was tested for breaking up the filter cakes and blending the wet and dry filter press batches to produce a more uniform feed.

Some additional carbon gasification rate determinations were made in a single hearth batch operated furnace.

Throughout this report, the reader will find various periods of operation referred to as "steady states." A steady state is defined by examination of the operating data and selecting the longest periods where no significant changes occur in the major operating variables, i.e. feed rate, hearth temperature and gas flows. An abbreviation such as IIB.3 (R) is used to refer to a specific steady state. Here "II" refers to the second campaign and "B" depicts the second part. ".3" specifies the third steady state period while "(R)" is used when a portion or a modified subperiod is referred to. In all cases each steady state period is described in detail in the appendix.

SECTION 5

RESULTS AND DISCUSSION

PYROLYZER

Description of Pyrolyzer Operation

Pyrolysis was accomplished in a pilot scale multiple hearth furnace consisting of six hearths, each 36" (.914 m) in diameter (Figure 5-1). A drawing of the furnace is incorporated in the flow sheet of Figure 5-2. Material is metered by a feed conveyor and enters the top of the furnace through a rotary star valve (Figure 5-3). The sludge is rabbled toward the center drophole of hearth one where it falls onto hearth two. It is again rabbled by rabble teeth outwardly toward the dropholes at the perimeter where it falls onto hearth 3 and so on down through the furnace. Final product exists through the chute of hearth six into a sealed drum where it is permitted to cool.

Each hearth is equipped with a metered natural gas/air burner, and a dampered exhaust breaching (Figure 5-4). All breachings are connected to a common manifold directing the gases to either the afterburner, above, of the cyclone-scrubber train to one side. The afterburner shown in the background of Figure 5-3 consists of a 70 ft^3 ($2m^3$) refractory lined chamber.

Split drafting is a technique by which some of the hot combustible pyrolysis gases are drawn downward through the furnace (Figure 5-5) while the remainder leaves through the hearth 1 exhaust. The purpose is to better maintain control of furnace gas and solids temperatures and atmosphere. It insures that there is a supply of unburned hydrocarbons above each hearth.

Basically, in the lower portion of the furnace the quantity of volatile material leaving the solids is small. At this point the char is approaching the final product volatile level. Without split drafting it is impossible to admit air to these hearths without reacting directly with the rabbled solids. However, heat is required to vaporize the small fraction of the volatile hydro-

carbons remaining in the char and to compensate for heat losses. One possible solution would be to supply the needed heat through a burner firing with an excess of fuel. This would prevent the air from directly reacting with the solids. This is of course undesirable from a fuel consumption standpoint. In split drafting the fuel supply is provided by drawing combustible gases from the center of the furnace down internally then adding the required air in the lower section to replace the required heat. The unconsumed hydrocarbons pass up through the split draft duct to rejoin the hearth 1 exhaust and pass onto the afterburner where combustion is completed.

Pyrolyzer draft is dependent upon the position of both the hearth one and bottom hearth dampers. In commercial operation the bottom damper would be controlled by a combustion analyzer such that the damper opens when added combustibles are required in the lower section of the furnace. This in turn sensitizes the upper damper to close maintaining the predetermined draft setting.

The pyrolyzer is amenable to automatic temperature controls. For example, if a quantity of excessively wet feed enters the steady operating pyrolyzer, the tendency to cool will be overcome by the automatic addition of air supplying the added heat required. Should the moisture content be above the autogenous point, the minimum fuel required will automatically be supplied.

Automatic controls will also compensate for a quantity of dry feed. In this case, the combustion air diminished and the added heat proceeds to the afterburner as combustible gases.

Pyrolysis Products

Three pyrolytic modes of furnace operation were studied, differing as to their products. These products are referred to as: low temperature char (LTC), high temperature char (HTC) and carbon burned ash (CBA).

LTC is the product of a pyrolysis where the bed solids temperature never exceeds 1200 ^{o}F (650 ^{o}C). It is a sterile, black, charcoal like, free flowing mixture of powder and granules. It contains all the ash of the feed sludge plus amorphous carbon and some non-putrescible material (volatiles). Maintaining this bed temperature prevents the volatilization of most toxic heavy

metals which are difficult or impossible to capture in most furnace air pollution abatement equipment.

HTC is produced at bed temperatures of 1600 ^{o}F (870 ^{o}C) or higher. It consists of basically fixed carbon and ash. Production of this char permits the highest furnace capacity.

CBA is produced by adding hearth area to the HTC mode furnace to react away the carbon from the HTC product. This results in minimum product weight and volume (like incineration) and maximizes the heat recoverable from the afterburner exhaust gases. The heating value of fixed carbon formed in the LTC or HTC process is added to the gas stream and not left in the solid product.

Char from a LTC pyrolysis run was further destroyed in a small single hearth pilot furnace. The results are illustrated in Figure 5-6 showing the increase in ash density as the carbon and volatile fraction is reduced. Densities range from .26 gm/cm^3 (16 lbs/ft^3) at 75% ash to .53 gm/cm^3 (33 lbs/ft^3) at 97.5% ash. High carbon char will settle somewhat with handling. This is its unsettled density.

Capacity

During all three campaigns the feed rate remained at 250+5 wet lbs/hr. (114+2 kg/hr). This feed rate was just under the design capacity for normal incineration and was selected to assure completion within the furnace. Hearth samples were then used in determining the area required for the various furnace zones.

In retrospect the optimum temperature profile for either HTC or LTC was not demonstrated. However, sufficient data have been obtained to predict a workable temperature profile and calculate capacities. Using the heat transfer and gasification rate data presented below, the overall furnace capacities for a vacuum filter cake of 22% dry solids, are calculated as 13 wet lbs/hr ft^2 (65 kg/m^{2}hr) for LTC, 15 wet lbs/hr-ft^2 (78 kg/m^{2}hr) for HTC and 12 lbs/hr-ft^2 (60 Kg/m^2-hr) for CBA.

For typical filter press cakes of 35% dry solids the wet feed rates do not change significantly (Table 5-1). However, on a dry basis the rate increases from 35 to 70% over that of vacuum filter cakes; see Table 5-1.

At this point in the technology development, one must consider these as maximum capacities. Appropriate design ranges must be applied to allow for changes in feed compositions and/or feed rate. When operating in the CBA mode one can confidently approach the maximum capacity. In this case a 20% fluctuation in feed rate to the high side will only cause a minor amount of carbon to appear in the ash. Likewise, when pyrolyzing in the HTC mode the same 20% change in feed rate will produce a product somewhat between HTC and LTC but in any case will always produce an unobjectionable product.

However, when operating in the LTC mode a 20% increase in throughput could result in uncharred material in the product. These uncharred portions have properties similar to dried sewage sludge and become malodorous once rewet. One added hearth should be used for the first several commercial LTC pyrolyzers.

The lower temperatures used in LTC make feed size reduction important. It has been noted during pilot operations that polymer conditioned cakes tend to form a dry crust hindering heat transfer to the center of large chunks. The longer residence time found in commercial furnaces will reduce this problem but feed size reduction is recommended.

Drying - Devolatilizing Zone --

This is the top zone of the furnace where the incoming sludge is heated from ambient temperature to about 200 ^{o}F (93 ^{o}C). At this point drying takes place. As drying proceeds devolatilization begins, first with low molecular weight, high vapor pressure organics followed by the heavier molecules as the sludge approaches the gas in temperature.

The area required for drying and devolatilizing is governed solely by the rate at which heat can be transferred into the solids. Variations in rate are controlled by changing the gas temperature as illustrated in Figure 5-7.

This figure shows a plot of heat transferred to the hearth bed plotted against gas temperature. The points were calculated from hearth sample checks of moisture and volatiles from Campaign III (Appendix C). There is no difference between incineration and pyrolysis with respect to drying and devolatilization, as heat transfer is mainly radiative in multiple hearth furnaces.

Fixed Carbon Gasification Zone --

In pyrolysis CBA operation, the final zone where the carbon portion of the char is reacted with CO_2 and/or water vapor the following reactions occur:

$$C + H_2O \rightleftharpoons CO + H_2$$

$$C + CO_2 \rightleftharpoons 2CO$$

These reactions are well known in the field of activated carbon manufacturing and regeneration. One important difference here is that in pyrolysis of sewage sludge it may be desirable to gasify the entire carbon fraction.

Gasification rates were determined in batch operation under various temperatures and atmospheres. Typically, the gasification rate remains independent of fixed carbon fraction until the ash limits the availability of carbon. Table 5-2, summarizing the data of Appendix D, illustrates the increase in gasification rate with increasing temperatures during the steady rate period. Also shown in Table 5-2 is that a rate decrease occurs when the fixed carbon level falls below 4 to 7%.

Energy Recovery

In order to determine the heat content of the furnace off-gas an overall system mass and energy balance is required. In doing a mass and energy balance for a period of time during a campaign where the operating parameters were relatively steady (steady state), the quantities diagrammed in Figure 5-8 must be calculated. The feed and product mass and heating values are measured, the product is assumed to be at hearth 6 temperature. Also measured are the fuel and air flows to the furnace and afterburner as well as their radiation and conduction losses.

A heat balance around the afterburner is used to ascertain the heat content of the furnace off-gas. Problems were encountered with leaks in the furnace, in large part at the feed chute (Figure 5-3). The furnace was run with a positive pressure, to eliminate dealing with unmeasurable air leaks. As a result, some of the hot furnace gases would escape without passing

through the afterburner. While the leak introduces errors into the mass and energy balances one can still calculate a reasonable off-gas heat content. The error in the heating value is smaller than that of the mass balance,and it will always understate the off-gas heating value. This is illustrated in Appendix B.

Gas chromatograph (GC) analysis of the pyrolysis gases proved uninformative. Samples were collected in plastic lined aluminum foil bags and transferred off site for GC analysis. Evidently the samples were high in hydrocarbons which condensed on the inner walls of the bags and therefore were not injected into the GC. Future GC work must be done on site without permitting the gas samples to cool.

The furnace and afterburner attain thermal equilibrium slowly and can absorb or release a few thousand BTU/hr while they are in flux, so longer steady states are preferred, for the heating value calculations. Steady states of 12 hours were desired, however, steady states as short as 5 hours had to be included.

There are eight (8) steady states that are five (5) hours long or longer for which the afterburner was on-line. (In one rejected case the afterburner was on-line but it received insufficient air for complete combustion.) The total energy out is within 10% of the total energy in for six (6) of these, if the leaks are ignored. Two examples of mass and energy balances are included in Appendix B. Table 5-3 summarizes the energy balances including the heat contents of the furnace off-gas and product heating values.

The net heat contents of the furnace off-gases shown in the Table 5-3 constitute the heat derived from the sludge with any fuel contribution subtracted out. Steady states IIB.1 (R) and III.5 were incineration and III.6 had some excess oxygen present, while the others are pyrolysis. The heat content, as measured in the pilot furnace, is about 50 BTU/ft^3 gases (120,000 J/kg) lower than what could be expected from a commercial sized furnace with its low radiation and conduction losses.

As illustrated above, considerable energy is available from the pyrolysis gases. Typically, when considering a waste heat

boiler the gases must be free of tars, oils and other condensible hydrocarbons. This gas stream can be obtained at the afterburner outlet. The quantity of heat that may be recovered is dependent upon the heat of combustion of the incoming sludge and feed moisture content. Clearly higher heat of combustion will provide higher recoverable heat. When the feed moisture content is greater than the autogenous point, the addition of fuel is required. A portion of this added fuel may be recovered as waste heat. Therefore, as the moisture content increases (above the autogenous point) so does the recoverable heat, but at the expense of the purchased fuel.

The off-gas heating values are calculated by standard engineering mass and energy balances. Appendix C contains summary sheets for each steady state providing the necessary information. It must be noted that the off-gas heating values are based upon a datum of 60 ^{o}F and liquid water.

To complete the energy balance the furnace and afterburner were tested for radiation and conduction losses. The equation for furnace losses based upon wall thickness, conductivity, and area is:

$$Q=a\ (1.5)\ \Delta\ T_1+\Delta\ T_2+\ldots+1.5\ \Delta T_6)$$

where the subscripts refer to hearths and a is 17.7 BTU/hr ^{o}F (33,600 J/hr - ^{o}C).

For the afterburner the linear relationship of $Q=b\ \Delta T$ is used where $b=\frac{67\ BTU}{Hr\ ^{o}F}$ (127,000 J/hr ^{o}C) for Campaigns

and $b=\frac{32.4\ BTU}{Hr\ ^{o}F}$ (61,500 J/hr ^{o}C) for Campaign III.

An insulating ceramic top replaced the steel afterburner lid in Campaign III.

Pollution Evaluation

Heavy Metals Studies--

Heavy metals accountings -- The feed preparation section clearly shows that the heavy metals in the sludge are concentrated in the filter cakes (Table 5-7) and therefore enter the pyrolyzer. Analyses of pyrolysis solid products showed that the heavy metals were not totally retained. Figures 5-9 to 5-15 show heavy metals retention plotted against a characteristic furnace temperature, the estimated maximum bed temperature which is the highest temperature the sludge solids see.

The estimation of the maximum bed temperature is explained in detail in Appendix A, but in brief, it consists of checking the hearth samples to see on which hearth the material was nearly finished drying and devolatilizing, as the solids cannot become hot until this is finished. The bed will then become at least as hot as the gases or hotter if there is oxygen present in the hearth's atmosphere. Thermocouples inserted in the dead bed of hearths 3, 4, and 5 during Campaign III verify the first assumption. Bed thermocouples do not record the bed surface temperature, they read cooler than the surface temperature when the surface is glowing from burning fixed carbon. It is estimated that the surface temperature is somewhere above 1200 ^{o}F (650 ^{o}C).

Figures 5-9 and 5-10 show the retention of copper and trivalent chromium (Cr^{+3}) vs. temperature. Copper averages 80% (range 60 to 100%)retention overall with no temperature trend evident in the scattered points. The Cr^{+3} retention with temperature averages approximately 90% but the data are very scattered. Since Cu and Cr^{+3} are basically retained independent of temperature, they are considered to be of low volatility.

On Figure 5-11 the nickel (Ni) retention shows very wide scatter. The atomic absorption test for nickel is less sensitive than that for other metals and the Coney Island raw sludge used in Campaign II contained barely measureable quantities. These points calculated to be much over 100% with a few in the 200% range. Rahway raw sludge used in Campaign III contained higher quantities of Ni leading to more accurate determinations. Here the retention averaged 81% placing this metal in the low

volatility range.

Figures 5-12 and 5-13 show the zinc (Zn) and lead Pb) retentions versus temperature. The retention of Zn drops from around 100% at 1300 ^{o}F (700 ^{o}C) to about 55% at 1700 ^{o}F (930 ^{o}C). While the retention of Pb drops from 95% below 1600 ^{o}F (870 ^{o}C) to values as low as 15% at 1700 ^{o}F (930 ^{o}C) and above. These metals are, therefore, considered volatile.

Figure 5-14 shows the cadmium (Cd) retention versus temperature. Below 1200 ^{o}F (650 ^{o}C) 45-70% of the Cd is retained. Above this temperature retention drops sharply to about 25%. The marked points on this figure are from Campaign II and are considered less dependable because they approached the lower detectable limit of analysis. Cd is therefore considered a highly volatile metal.

Figure 5-15 shows that mercury (Hg) is volatilized almost completely at temperatures above 1100 ^{o}F (600 ^{o}C). Over 7% of the mercury was retained in a few of the low temperature runs, but the retention was 1% at temperatures above 1300 ^{o}F (700 ^{o}C). Hg is therefore considered a highly volatile metal. Previous workers* have stated that 50% of the incoming Hg would be retained in the furnace solid product. The above data clearly contradicts this finding.

Attempts were made to measure some other metals in this work. Beryllium remained below a detectable limit of 2 mg/kg in this testing. There is indication that arsenic is a volatile metals from Campaign I, but the data are either at or below their detectable limit, deterring any conclusions. Cr^{+6} also remained below detectable limits ($\leq$ 4 mg/kg); in no case was Cr^{+3} oxidized to Cr^{+6} in the furnace, although Cr^{+3} was present at 200-1100 mg/kg. This was true for incinerations, as well as pyrolyses.

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*"Air Pollution Aspects of Sludge Incineration"
EPA Technology Transfer, 1975

An additional high temperature test was performed. Product char was heated in a tube furnace to 2000 ^{o}F (1090 ^{o}C) for nearly 15 minutes. These conditions were sufficient to evolve nearly all of the lead, zinc and cadmium, whereas the chromium copper and nickel were retained.

Considering all the data,the metals can be ranked into three categories, low volatile, volatile and highly volatile.

LOW VOLATILE	VOLATILE	HIGHLY VOLATILE
Cu	Zn	Cd
Cr^{+3}	Pb	Hg
Ni	As (?)	

Table 5-4 shows the heavy metal accounting in Campaign III where Andersen and EPA-5 tests were taken of the afterburner stack gas. The Andersen samples provide the particle size distribution along with enough particulate to determine heavy metals concentration. However, the EPA-5 sample train is required to determine particulate loading. The combination provides a measure of the total hourly flow of heavy metals, leaving the pyrolyzer in the gas stream.

A program to locate the unretained heavy metals was undertaken. For several steady state conditions of Campaign III gas samples (Andersen particulate catch), furnace products, cyclone catch and scrubber effluents were analyzed for their heavy metals content.

Table 5-4 shows that all attempts to close the heavy metals balances, specifically for Cd and Hg has been unsuccessful. The feed and solid product heavy metals analyses, have proven reproducible throughout all three campaigns. Extensive investigations of the metal contents in the gas stream leaving the pyrolyzer was beyond the scope of this study. However, the cursory study carried out and discussed below qualitatively supports the thesis that the unaccounted for metals exist with the furnace gases.

Stack heavy metals concentration vs. particulate size -- A brief study was made to determine the quantity of heavy metals in the stack particulate matter (Appendix C). It was found that Cd, Zn and Pb often were in higher concentrations in the

Andersen and cyclone catches than they were in the furnace solid products. This indicates that some of the particulates are volatilized metals rather than entrained ash.

Analysis of EPA-5 and Andersen catches found the Cd, Zn, and Pb are of highest concentration in the fine particles. Each of the Andersen plates was washed with acetone to remove the amounts of particulate. These and the final filter catch were analyzed for heavy metals. The relative concentration of metals in these two samples gives some indication of associated particle size. Most of the copper and iron captured was in the plate wash sample, while most of the zinc, cadmium and lead captured was in the smallest particles caught by the final filter (on the order of 0.2 μm). These analyses were done by atomic absorption.

Andersen samples were taken of the furnace off-gas of a 1450 ^{o}F (790 ^{o}C) pyrolyzer. The results of X-ray fluorescence tests on these samples are presented in Figure 5-16. Iron, aluminum and copper appear mainly in the larger particle sizes; this is in agreement with the above atomic absorption determinations. Lead is evenly distributed among the size ranges while zinc appears to be more concentrated in the larger particles. These results are inconsistent with those of atomic absorption, however, this one sample should not alter the conclusions drawn from the eight atomic absorption samples.

Glassing over at high furnace temperature -- At temperatures at and above 1650 ^{o}F (900 ^{o}C) the ashes sinter in the furnace and some of the metals become fused in a glass. There was a puzzling absence of chromium in high temperature furnace ash samples made in Campaign I, which were digested for atomic absorption in aqua regia. Upon further analysis of the samples, digesting in HF, it was observed that all of the chromium was present in the ash once the glass was dissolved.

Figure 5-17 shows the ratio of metals detected by HF and aqua regia digestion and atomic absorption analysis indicating the amount of metal captured in glass. The glassing over takes effect above 1600 ^{o}F (870 ^{o}C) and affects metals by varying amounts at 1800 ^{o}F (980 ^{o}C) the HF method detects twice as much zinc, 1.5 times as much lead, and 3 to 7 times as much chromium compared with the aqua regia method. Copper is nearly the same when done either way and is apparently not "glassed over".

Stack Particulate Evaluations--

Table 5-5 summarizes the results of the particulate tests done at the afterburner stack in this project. The third column is the total weight of particulates measured by the EPA-5; the afterburner always appears to remove a large amount of particulates probably by burning carbon. The next column is the average particle diameter derived from the Andersen measurements adjusted to the mass-mean particle diameter, based on a particle density of 3.2 gm/cm^3. The last column is the fraction of material smaller than 1 μm in diameter.

Particulate emissions vary mainly with the gas throughput in a furnace. In the updraft pyrolysis runs, providing small gas flows, the emissions were 0.9 to 2.3 lbs/dry ton (0.45 to 1.2 kg/dry MT). In the two updraft incinerations in Campaign III, where the excess air input was high providing large gas flows, the particulate loadings were 5.6 to 6.3 lbs/dry ton (2.8 to 3.2 kg/dry MT). The two split draft pyrolysis runs in Campaign III with low gas flow rates also had low unscrubbed particulate loadings at the afterburner stack, 0.8 to 2 lbs/dry ton (0.4 to 1 kg/dry MT), but it is also true that the furnace solids were wet on all but 1½ hearths, allowing little space for entrainment of fine particles.

No correspondence could be found between average particle size and conditions occurring in the furnace. In Campaign III one case of updraft incineration has < 0.2 μm average particle size and another case has a 5.8 μm average. The two Campaign III split-draft pyrolysis cases have < 0.2 and 0.5 μm average particle sizes. Nearly all of the Andersen particulate weight fractions conform well to a log normal distribution, (Appendix C) which is typical for particulate samples.

There may be a connection between furnace temperature and the amount of smaller particles. In Figure 5-18 the amount of particles smaller than 1 μm at the afterburner stack is plotted against the maximum bed temperature. The lowest values are at the 1200 °F (650 °C) temperature. This implies that these small particles are vaporized from the hotter bed.

Toxic Organics --

The feed preparation section shows the presence of pp 'DDE, Dieldrin and PCB in the feed to the furnace in concentrations of less than 6 mg/kg. Both pyrolysis and incineration removed all measurable traces of these toxic organics from the solid product.

However, it cannot be concluded that they were totally destroyed. Stack samples are reported as <1 mg/kg which is expected due to the very low feed concentrations. More sensitive stack analyses must be used before a conclusion can be made.

FEED PREPARATION

Dewatering Practice

One of the major objectives in pyrolysis is fuel savings. Clearly, the largest fuel requirement is drying the sludge prior to burning. When one examines the alternatives for removing water from sewage sludge there are many; settling, centrifuging, vacuum filtration, various types of belt filters and filter presses. Among these the filter press with expandable diaphragm plates, is the most practical piece of equipment.

Most sewage sludges are rather dispersed suspensions which are difficult if not impossible to filter without conditioning. Two forms of conditioning are in common practice today. Coagulation with ferric chloride and lime is accomplished by dissolving ferric (sometimes ferrous)chloride into the sludge then neutralizing the solution with lime. The gelatinous precipitate formed coupled with large quantities of excess lime result in flocculation of the sludge. The flocs formed by ferric and lime conditioning are very small and result in no apparent physical change in the sludge. However, the filterability has changed markedly.

Polyelectrolytes (polymers) are also used. Here, long chain polymeric molecules incorporate electrostatic charges which gather and flocculate dispersed sludge particles. The physical results are somewhat akin to curdled milk; large flocs are formed leaving clear, solids-free liquid between.

A choice of conditioner must be made, assuming both will adequately dewater the sludge. The key ratio for heavy recovery is BTU/#water. This is the ratio of heat available upon combustion of the solids to the heat absorbed by the evaporation and super heating of the water. When one compares a given sludge conditioned by each method resulting in cakes dewatered to the same net moisture content the polymer conditioned sludge will have the more favorable BTU/#water ratio. This is attributable to the fact that the ferric and lime conditioned cake has the burden of evaporating the water associated with the excess lime.

This study proved that polymer conditioning and the use of a filter press with expandable diaphragms to squeeze the cake after it was deposited in the press was a very good way to dewater sewage sludge to a high solids concentration. In many cases the solids were above the percentage required to have autogenous operation (without fuel added) in the multiple hearth pyrolysis unit.

Process Flow Sheet

The process flow sheet is shown in Figure 5-19. This is the final version used in Campaigns II and III after modification to overcome difficulties experienced in Campaign I. Sludge is unloaded from a tank truck through a pug mill that removes rags and stones and mixed a conditioning chemical into the sludge. For polymer conditioning, the conditioning chemical is predissolved high cationic polyelectrolyte from a storage vat. For lime and ferric conditioning, ferric chloride solution from a storage vat is mixed with the sludge in this pug mill. The sludge is then pumped into a tank where a compressed air lance kept it well mixed. For lime ferric conditioning, lime is added in batches to this holding tank to complete the conditioning of the sludge. The sludge is delivered into the filter press by a diaphragm pump. When the inlet pressure to the filter press rises to a pre-determined level for a particular experimental run (generally between 70 and 90 psi) the pump is turned off. The filter press trays have expandable rubber diaphragm surfaces and these are expanded by compressed air so as to diminish the space between filter trays and thus squeeze the cake. The compressed air pressure was approximately 100 psi (690,000 N/M^2). The time of application of this compressed air ranges from 5 minutes to 15 minutes being varied in a pre-planned manner. The

compressed air is then turned off and the filter trays drawn back one by one to release the cake into a hand cart. Cakes are sampled individually as they are dropped. From the hand cart cakes are shoveled into drums which are stored for 1 to 4 days before being used as feed to the pyrolyzer.

The heart of the dewatering scheme is the filter press. Basically, it consists of a number of plates or trays which are held rigidly in a frame to ensure alignment and are pressed together electro-mechanically between a fixed and moving end. Figure 5-20. On the face of each individual plate is mounted a filter cloth. The sludge is fed by a diaphragm pump into the press and passes through center feed holes in the trays along the length of the press until the cavities or chambers between the trays are completely filled. The sludge is then entrapped and a cake begins to form on the surface of the cloth. The water passes through the fibers of the cloth, but as the solids are coarser than the voids in the cloth they remain on the face (Figure 5-21). The rubber face of the press plate itself has raised buttons on it so that the water or filtrate can drain.

Conventional filter pressing requires relatively long cycle times; 2-4 hour cycles are common. Examining the filtrate-volume versus time curves in the literature it is evident that over 60% of the solids are passed into the press during the initial 25% of the cycle's length. The remainder of the cycle can be accelerated greatly by mechanically squeezing the cake between expandable diaphragms.

Briefly, expandable diaphragms can be visualized as a movable plate in a conventional plate and frame filter press. Once the rapid filtration portion of the cycle is complete, force is applied forcing the plates toward one another wringing the water from the cakes.

In practice the diaphragms are formed over steel recessed plates and hydraulic or pneumatic force is used between the plate and diaphragm to separate them compressing the cakes.

During this study it was found that the diaphragms reduced the total cycle length to 1/3-1/2 of that required by the conventional press. In most cases under conditioning could be compensated for by prolonging the length of the compression. Naturally, the cakes formed in this manner were in-

ferior to those of proper conditioning, however, they were dry enough to handle.

A 4' X 4' pilot filter press Figure 5-20) performed the filtering for the 3 campaigns of pilot scale pyrolysis testing/ The press was equipped with expandable diaphragm type trays for Campaign II and III only, and with rigid trays for Campaign I. The total filtering area is 225 square feet (21 m^2). The rigid trays were spaced to produce a cake 1.25 inches thick. The expandable diaphragm-type trays were spaced so that the filter cake thickness would be 1.13" (2.87 cm) if the diaphragm did expand (and thus squeeze the cake thinner), but in actual practice the average cake thickness varied from 1.13" (2.87 cm) to 1.100" (2.54 cm). The rigid tray test produced approximately 1300 lbs. of wet cake at about 32-35% moisture in a roughly 3 hour cycle (Coney Island digested sludge). The expandable diaphragm equipped press produced 1100 to 1300 lbs. (200-500 kg) of wet filter cake at approximately 30-45% moisture on a roughly 1.25 hour cycle (Coney Island raw sludge and Rahway Valley raw sludge). However, it must be noted that the preceding rough figures are a comparison among various sludges. This report does not cover a detailed study of diaphragm plate filter pressing versus conventional plate filter pressing.

Filter Press Performance

Initial Work--The preliminary work consisted of testing a number of sludge samples for filterability and heating value. Both ferric-and-lime and polymer conditioning were tested. The capillary suction timer (CST) was used to seek a workable ferric and lime dosage. Visual floc examination was used to locate an acceptable polyelectrolyte level. Neither conditioning agent was studied in depth. The results are possibly maximum cake solids but certainly not the economic optimum regarding conditioner consumption.

Table 5-5 summarizes the results of the preliminary dewatering experiments covering four plant locations including both raw and digested sludge. Filterability was tested in a one square foot filter press (lacking expandable diaphragms). Sludge samples were judged mainly on the basis of resulting cake solids.

Based upon these initial data Coney Island raw, Coney Island digested and Rahway raw sludges were selected for furnace pyrolysis.

Pilot Filter Press Results--

Filter cake solids content--Campaign I was fed Coney Island digested sewage sludge. Both ferric chloride and lime and polymer were used as a conditioning agent. Cake solids averaged (35.4±2)% and (31.8±2)% respectively with standard recess plates.

Campaign II parts A and B were each fed Coney Island raw sludge. Here also both ferric chloride and lime and polymer were used to condition portions of the sludge. Cake solids averaged (40.3±3)% and (41.2±4)% respectively with expandable diaphragm plates.

Campaign III used Rahway raw sludge as the feed material. Only polymer was used to condition this sludge and resulted in an average filter cake of (31±3)% solids with diaphragm plates.

Heavy metals content of filtrate and cake--In Table 5-7 heavy metal concentrations in the filtrate, based on averages of 2-7 tests, are compared with those in the filter cake, both on a wet basis. It is clear that the metals are almost completely contained in the solids.

BOD, toxic organics and other filtrate measurements--Other measurements made on the filtrates were phosphate, total carbon (TC), total organic carbon (TOC), pp'DDE, Dieldrin, PCB, nitrate, nitrite, total Kieldahl, nitrogen (TKN) and BOD_5 levels. The average of 2-7 values are tabulated in Table 5-8.

The type of conditioner used affected the filtrate. The high alkalinity of the ferric and lime treated sludge reduced the soluble phosphorus to a tenth of that in the polymer conditioned sludge filtrate. The polymer conditioned sludge filtrate contained several hundred mg/l more TC than the ferric-lime conditioned filtrate. The BOD_5 was not very much affected by conditioner.

Both TC and phosphate must be considered a recycle pollution load to the head of the treatment plant and, therefore, considered in the overall plant scheme.

Toxic organics are shown in Table 5-8 to be concentrated in the filter cake. Trace quantities of pp'DDE and Dieldrin were found only in Campaign II filtrate. All other filtrates are reported as nil.

Cake Breaker

It was sometimes necessary, depending on the consistency of the furnace feed, to mechanically reduce in size the pieces of filter cake to prevent unburned lumps in the product. Small pilot furnace dropholes can also clog with large lumps, although this would be no problem in a large furnace.

Two cake breakers were tested in the pilot program. The first type worked well on dry filter cakes, such as those from Coney Island raw sludge; as it contained rotating blades to shred the filter cake. Because the Rahway sludge was sticky a different device was used; two motor-driven rollers squashed the filter cakes to give small pieces.

The cake breaker also served to mix the filter cake for a more uniform feed. Filter cake moisture varied among filter press batches. In Campaign III wet batches were blended with dry batches producing a more uniform feed moisture content.

SECTION 6

CASE STUDY OF AN INCINERATOR CONVERSION

Many sewage sludge incinerators currently exist. Of major interest is the feasibility and economics of converting these installations to pyrolysis units. Naturally, each incinerator installation has some unique features, location, size equipment arrangement, etc. However, all have much in common.

To make a meaningful conversion estimate, a specific incinerator was selected. It is assumed that since this installation is typical of others in the field, the cost figures will be roughly accurate for other similar installations.

DESCRIPTION OF PRESENT INCINERATOR

The incinerator chosen for this study is a 22'3" (6.78 m) outside diameter 10 hearth multiple hearth furnace. This is an indoor installation having a local instrument control center. The feed sludge is vacuum filtered to about 22% dry solids in a separate building and conveyed to the furnace on open conveyor belts. The resulting ash is cooled within the furnace, lifted by a bucket elevator to a screw conveyor where it passes into a truck to be hauled to an offsite land fill.

The incinerator itself has no automatic controls. Each of the six oil burners has fuel/air ratio controllers but the firing rate is manually controlled. The air supply for combustion of the sludge is drawn into the furnace by the I.D. fan. Combustion air volume is controlled by hand operated dampers on the hearths in the lower half of the furnace. To supplement this air the center shaft cooling air is also passed into the lower portion of the furnace.

The incinerator off-gas treatment on this unit consists of a gas pre-cooler and a low pressure drop cyclonic scrubber. The scrubbed gases are passed through the induced draft (ID) fan and exhaust to the atmosphere.

DETAILS OF INCINERATOR CONVERSION & COST ESTIMATE

For this study pyrolysis to LTC was chosen because of the high heavy metals content common in the regional sludges investigated. The changes necessary to convert a typical 22'3" (6.78 m) outside diameter x 10 hearth incinerator to a pyrolyzer have been specified.

The proposed design omits a boiler from the gas handling system. A boiler is useful only if the plant has some specific need for steam, and each situation must be considered separately. The work includes the following changes and additions.

1. Sealing furnace
   To control the atmosphere within the pyrolyzer all major air leakage must be stopped. This will require labor and miscellaneous materials to caulk the butt straps and vertical furnace seams, make minor repairs to doors and burner boxes and to seal the bottom plate. Also included are modifications to the top and bottom center shaft sand seals and the additions of an air tight feed chute.

2. Split draft duct
   A split draft duct is needed to remove hot combustible gases from hearth 10 and convey them to the hearth 1 exhaust. It is refractory lined and insulated for personnel protection and includes a full dimension clean-out port at hearth 10 level.

3. Dampers
   Two air cooled and refractory-covered automatic dampers are required at hearths 1 and 10. They control the relative split of hot gases as well as the overall furnace pressure.

4. Burner modifications
   Presently the furnace has six manually controlled, oil fired burners. Three of these burners, one on each of the presently fired hearths must be modified with gas pilots and automatic air supply valves. All the present

air to fuel ratio controllers must remain. The three remaining manually controlled burners will remain. These burners may be used during start-up or during periods of extremely wet sludge.

5. Injection air fan

   An injection air fan is required to supply the necessary pyrolysis air at a controlled pressure. A typical incinerator would have manual dampers outside the furnace to admit its large excess air requirement. A pyrolyzer requires a more controlled air supply. Included here is a 10,000 CFM 8 osi fan complete with motor and foundation.

6. Injection air piping
   The injection air piping is designed to handle up to 1/3 of the total air required to any one hearth (on each of six hearths). The exact injection air profile depends on the volatile and carbon content of the sludge. Included is the pipe, valves and installation labor.

7. Afterburner
   The afterburner is the largest single item to be installed in the design. It has an interior volume of 500 ft^3 (14 m^3) allowing a 1/2 second residence time. It is complete with an automatic oil burner including gas pilot air and fuel lines. The hot pyrolysis gases enter tangentially to make efficient use of the afterburner volume. This includes purchase of material and on-site construction, labor and building changes for support and access provision.

8. Emergency gas outlet stack
   The present emergency by-pass stack will be relocated atop the afterburner. Relocation includes building modifications for support and access.

9. Quencher-scrubber
   The present quencher and cyclonic scrubber will be reused. Both units must be relocated including the duct work to carry the afterburned gases to the quencher and scrubber. Item includes building alterations.

10. Char cooler
    A paddle type cooler will cool the product LTC from 1200 ^oF to about 300 ^oF and convey the char to the present bucket elevator. This includes modifying furnace outlet, installation and water supply piping.

11. Instrumentation

A full complement of instrumentation is included in the estimate. A combustibles analyzer and controller measure and controls the combustibles level on hearth 10 by modulating the control damper on the split draft duct. Temperature controllers regulate the gas temperatures on six hearths by adjusting the injection air control valves. The injection air is separate from the burner air system. Some equipment is necessary to convert the manual burners to automatic control. A new instrument panel augmented with a second strip chart temperature recorder is included. This item includes the purchase and mechanical installation of:

(a) Combustibles and oxygen analyzer
(b) Automatic draft controller
(c) Damper control motors
(d) 6 temperature controllers
(e) 6 valve regulating motors
(f) New 10 point temperature recording strip chart.
(g) Paddle cooler temperature controller
(h) Instrument panel addition
(i) Miscellaneous pressure and draft gauges

12. Wiring

This item includes wiring for two added motors, their starters and that required for all instrumentation.

To the above items painting and a modest contingency of 5% are added bringing the total to $400,000 as shown on Table 6-1.

In many cases the present incinerator must be updated by the addition of an afterburner. For this installation an afterburner installation would include items 7, 8, 9 and a portion of the instrumentation, piping and wiring for a total approximate cost of $200,000.

THERMAL DESTRUCTION FUEL REQUIREMENTS

Fuel requirements for various modes of thermal destruction presented in Table 6-2, were determined on the basis that all systems require an afterburner. The afterburner consumes all fuel present at 15% excess air and gases exit at 1400 ^{o}F. This allows a one-on -one comparison of all modes of operation. It is clearly shown that pyrolysis modes yield significant fuel savings over incineration.

Parameters established for heat balance calculations were:

a) 25% ash in dry solids
b) 75% combustibles in dry solids
c) 15% of the combustibles yield fixed carbon
d) Heating value of solids - 10,000 BTU/lb. organics
e) Afterburner conditions - 15% excess air with 1400 ^{o}F exit temperature.

ECONOMIC DEVELOPMENT

Changing from vacuum filters to filter press:

A. Increases capacity expressed on a dry solids basis.
B. Decreases or eliminates fuel consumption

Table 6-3 shows the combined effect of these factors in relation to a 22'3" X 10 hearth incinerator. It shows for three different drynesses that the cake might reach the fuel cost per ton of dry solids and the cost of amortizing the various filter press investments required as the tons of dry solids handled per day through this size furnace increase. The total of fuel and filter press amortization costs decreases sharply as the cake gets dryer. It is assumed in this approach that the operating and maintenance costs per ton of dry solids would remain the same as for the existing vacuum filters, for various size filter press installations. This tabulation still neglects some benefits since it does not reflect the sharply

lowered incineration costs that come about as the same annual operating labor and main cost and equipment charges are spread over up to 2½ times as much as dry solids.

Table 6-4 presents similar figures for LTC pyrolysis again showing greatly reduced total costs of fuel and amortization of filter press plus conversion to pyrolysis as cake moisture is reduced.

The point of these two tables is the comparison between them which shows that conversion to LTC pyrolysis saves $5 to $8 per dry ton at all cake moisture levels through 39% solids. At 39% solids pyrolysis has become practically autogenous. Getting a dryer cake cannot further reduce the fuel cost per ton for pyrolysis. Therefore as the cake solids increase to about 47% solids (where incineration fuel cost also disappears) the saving of pyrolysis as compared to incineration diminishes and in fact at 47% becomes slightly negative because of the cost of converting the equipment from incineration to pyrolysis.

The above comparison however also neglects the higher capacity of a given size multiple hearth furnace operated in the pyrolysis mode as compared to the incinerator mode. Were new installations rather than a conversion under discussion, the higher throughput rates in dry tons per day shown for pyrolysis in Table 6-4 would mean reduced furnace size and purchase cost. Even under consideration of conversion, increased throughput rates may reduce operating costs by reducing hours of work per week or allowing expanded capacity when required without the purchase of new equipment or use of additional labor.

Table 6-5 attempts to eliminate the variable capacity from comparison of Tables 6-3 and 6-4. It shows the years required to recoup the capital investment for conversion to pyrolysis of 22% solids vacuum filter cake and the years required to recoup the larger investment for addition of filter presses as well as conversion to pyrolysis. In this Table it is considered in all cases that the throughput will be limited to the same dry tons of solids per year as could be handled when the furnace incinerated 22% moisture cake.

Again no credit is taken for possible shorter hours of operation or the availability of additional furnace capacity should plant expansion be required.

Payout time is established in the data presented in Table 6-5 showing the added cost for a constant capacity pyrolyzer. The case study is based on an established incinerator handling 21,800 tons of dry solids per year from a 22% solids sludge cake. For these conditions it has been shown to have a total added cost of $40.90/dry ton in Table 6-3 (fuel cost plus added capital investment). On this basis, payout time for 22% dry solids would be approximately 2.4 years. If the present vacuum filters are discarded (at zero salvage value) and filter presses are installed to dewater the 3 to 5% sludge the payout period will grow to approximately 3 to 4 years. Although this is a longer period for the investment return the net annual dollar savings is greater. Since the annual costs are on a continuously inflating basis, the filter press becomes the most attractive alternative.

It appears that conversion of existing incinerators to pyrolysis with or without a change to filter press dewatering is an investment that can be easily justified by reduction in cost of fuel. It is also an investment that would contribute to reduction in energy consumption for sludge disposal.

The potential for reaching zero fuel consumption when pyrolysis is applied in conjunction with filter presses (another profitable investment) should not be overlooked as it seems doubtful that filter pressing alone could produce a dry enough cake to bring incineration to zero fuel consumption where afterburning is required.

FIGURE 5-1

HEARTH SAMPLING DURING A PYROLYSIS RUN

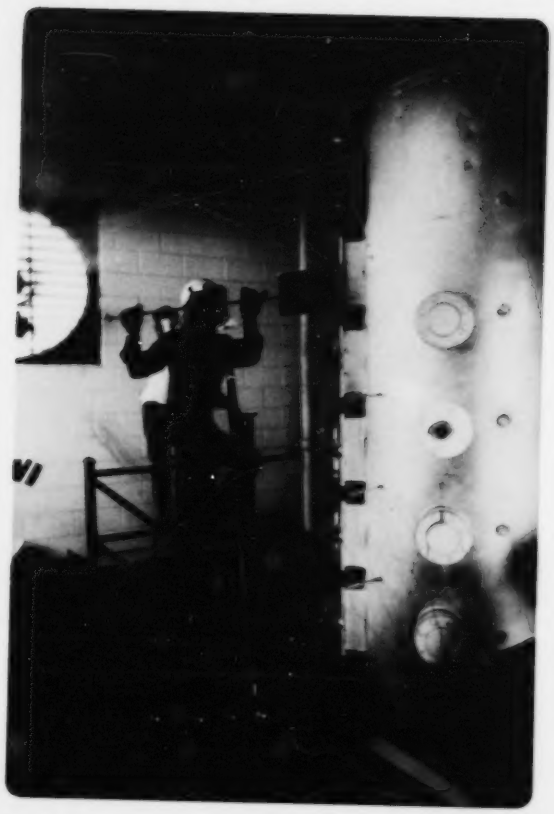

FIGURE 5-2 FURNACE FLOW SHEET

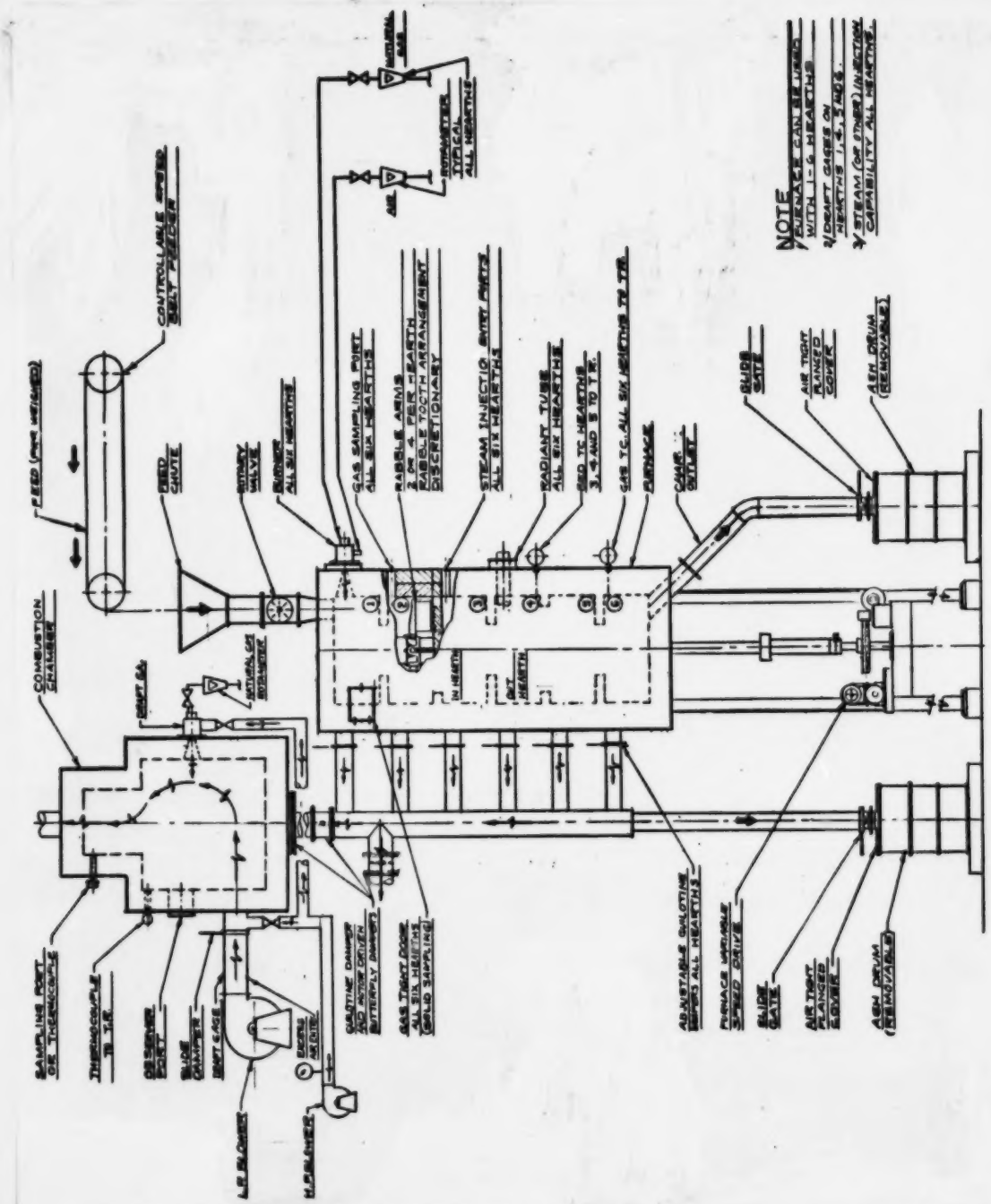

FIGURE 5-3

FOREGROUND: FEED BELT AND FEED HOPPER
(See Text)

BACKGROUND: AFTERBURNER

FIGURE 5-4

FURNACE MANIFOLD WITH BREACHINGS & DAMPERS

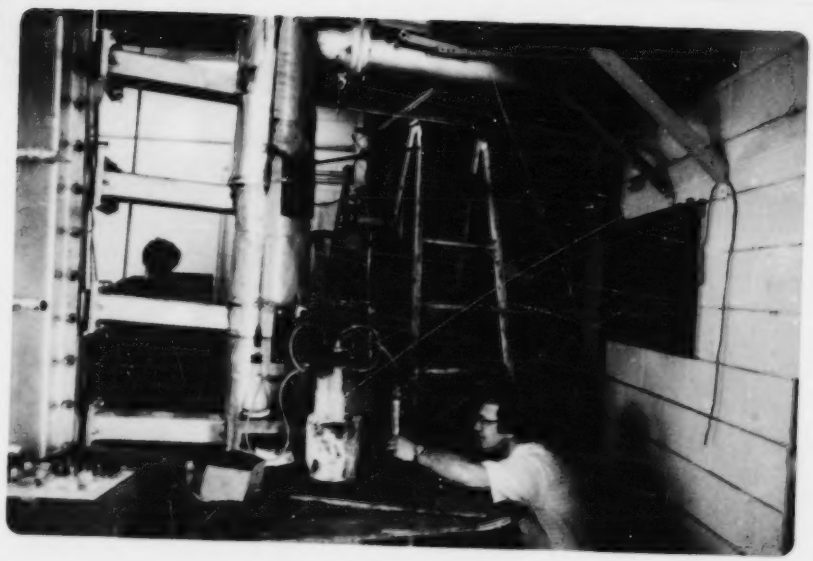

FIGURE 5-5

VOLATILE FLAMES DURING
SPLIT-DRAFT PYROLYSIS

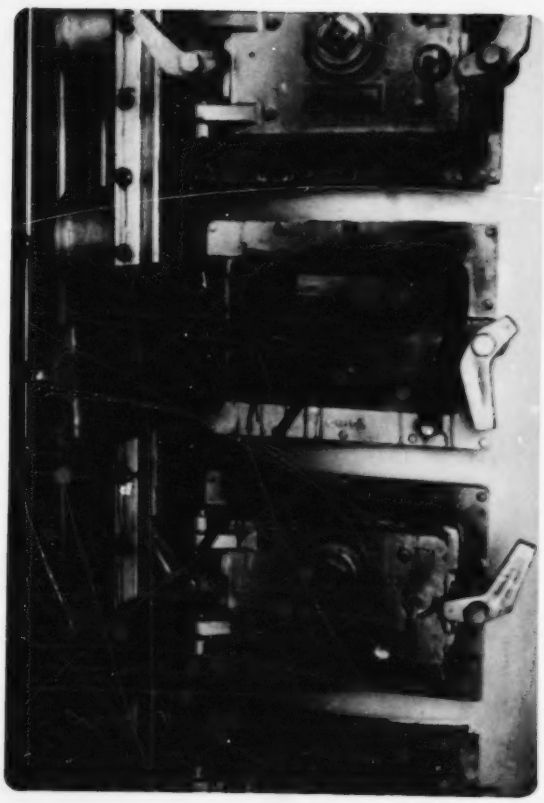

FIGURE 5-6 ASH DENSITY VS. % ASH

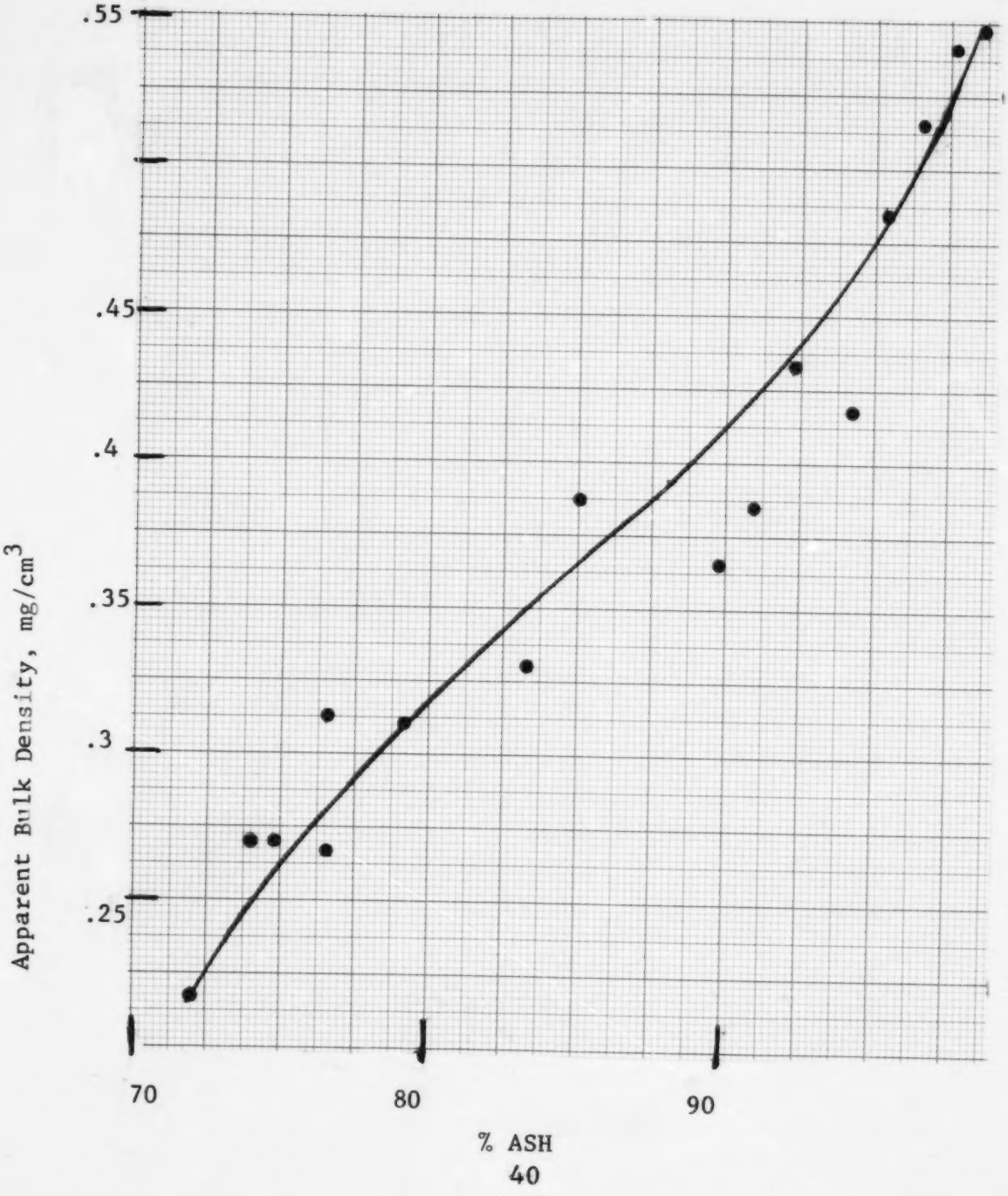

FIGURE 5-7: DRYING & DEVOLATILIZING RATE (CAMPAIGN III DATA)

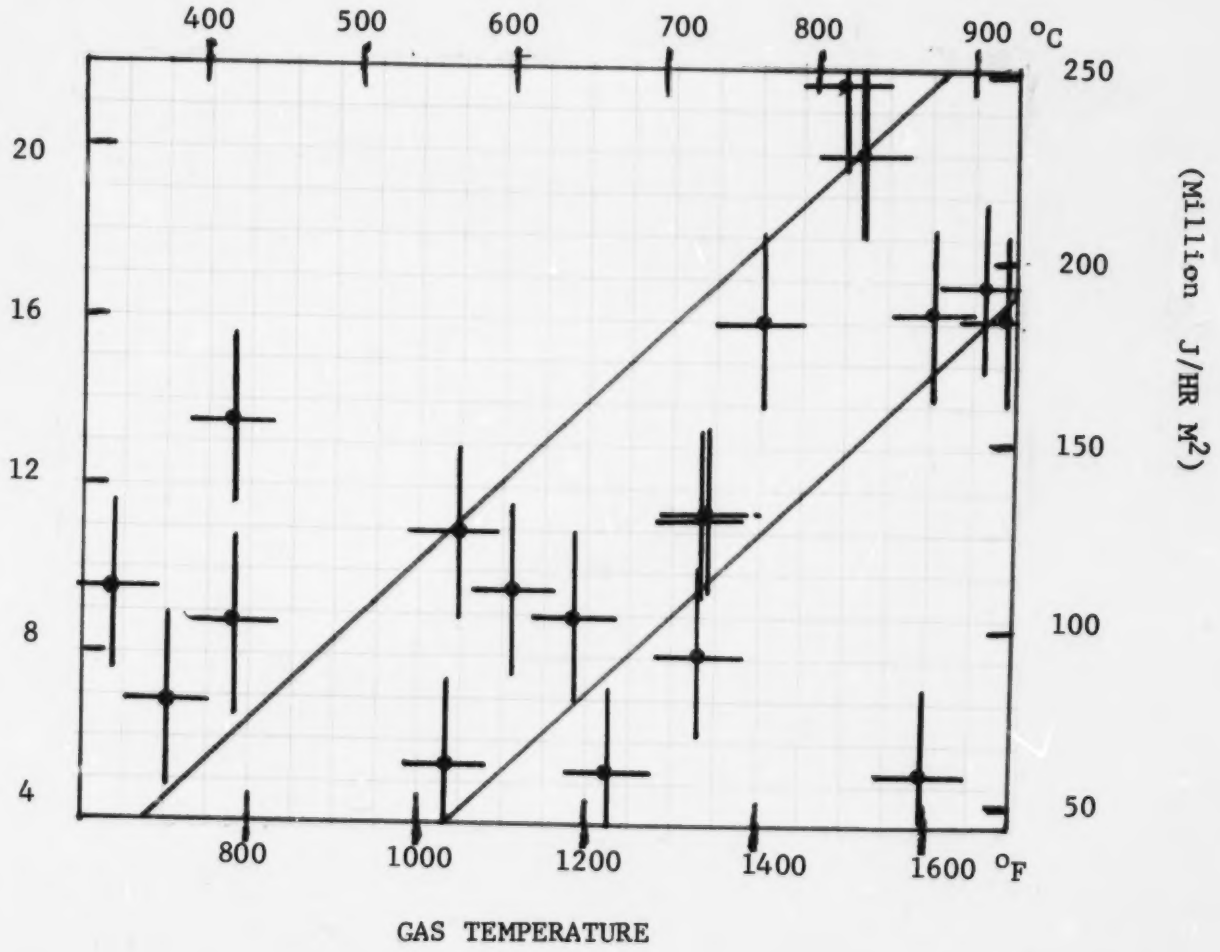

FIGURE 5-8: HEAT BALANCE FLOWSHEET

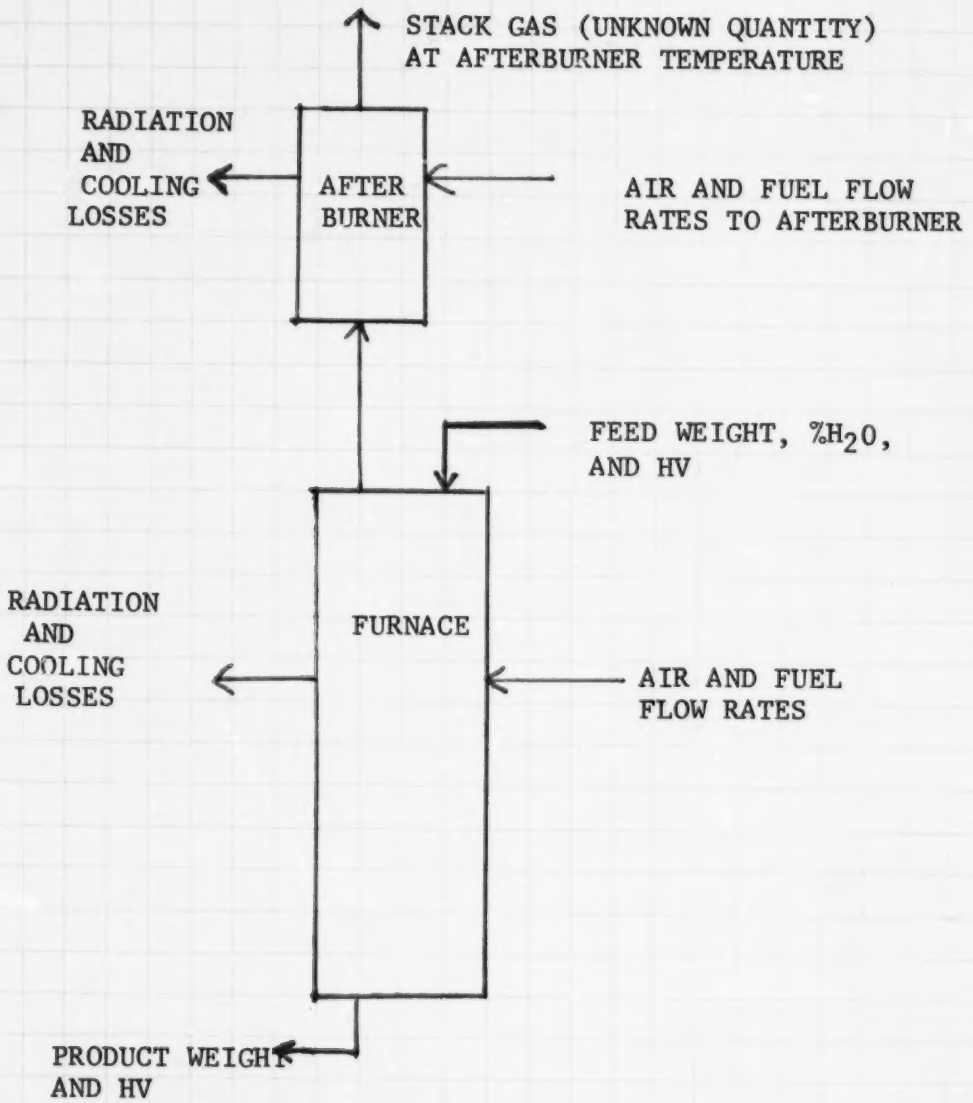

FIGURE 5-9 PERCENT CU RETAINED

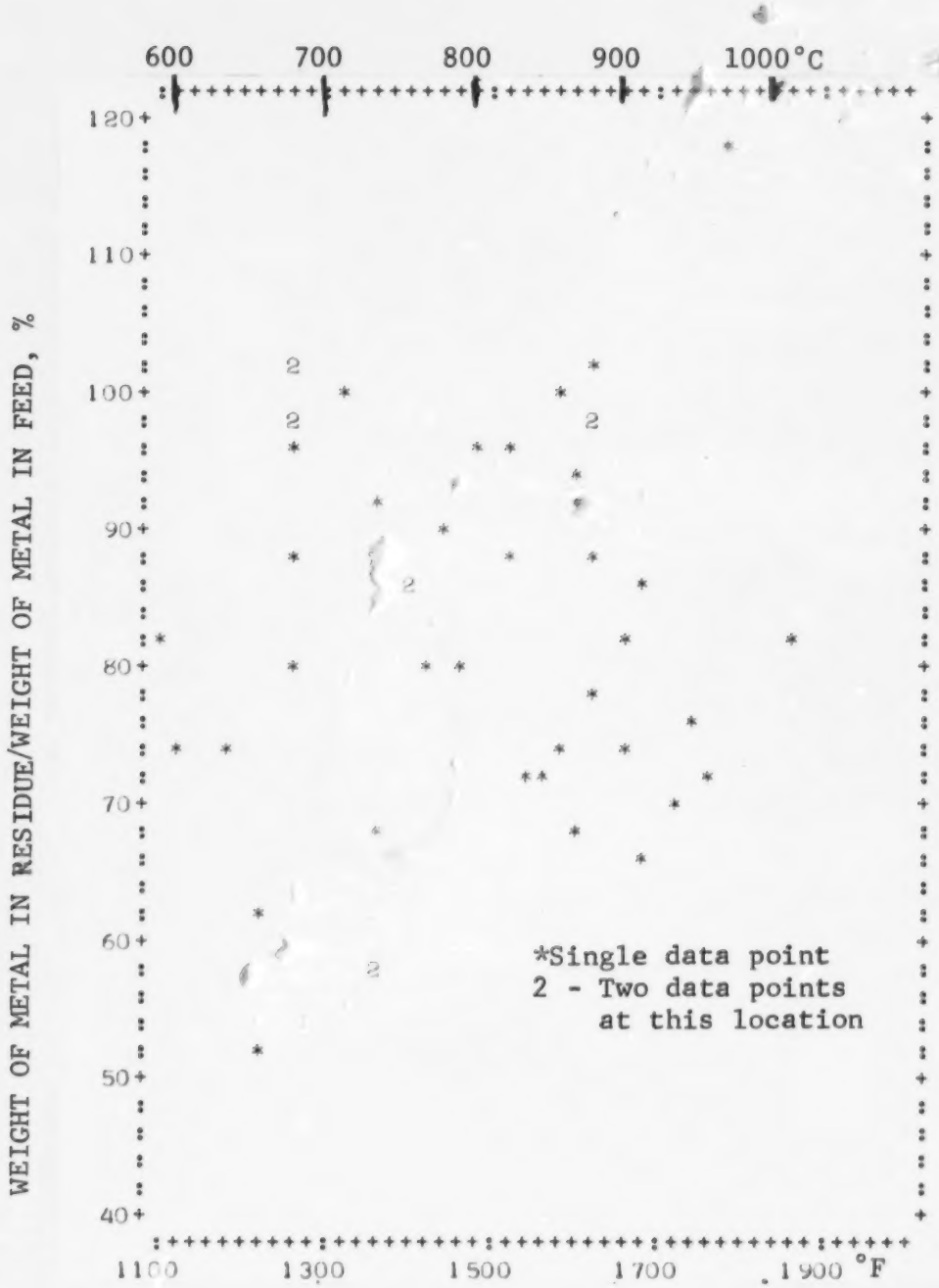

FIGURE 5-10 PERCENT CR RETAINED

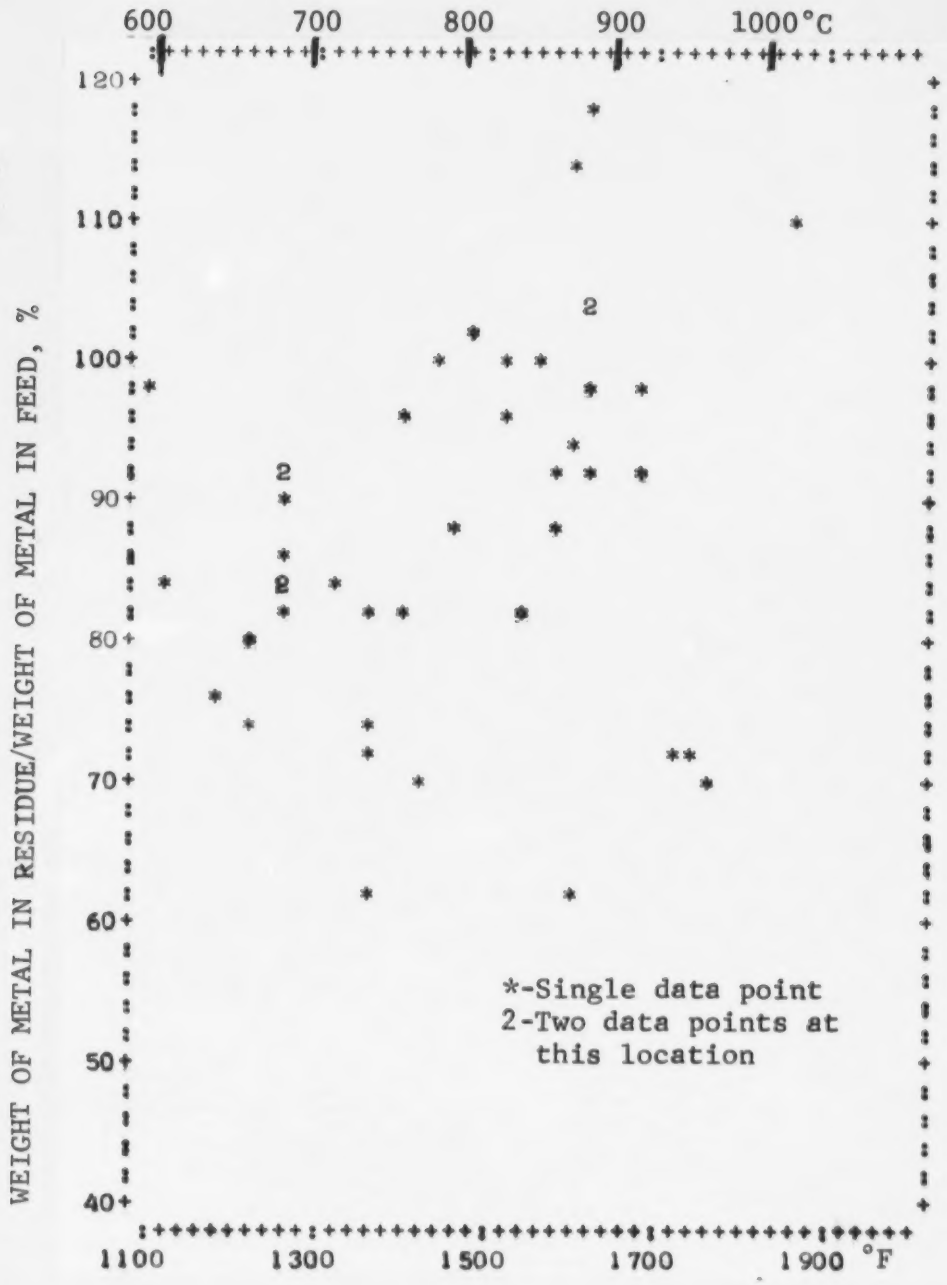

FIGURE 5-11 PERCENT NI RETAINED

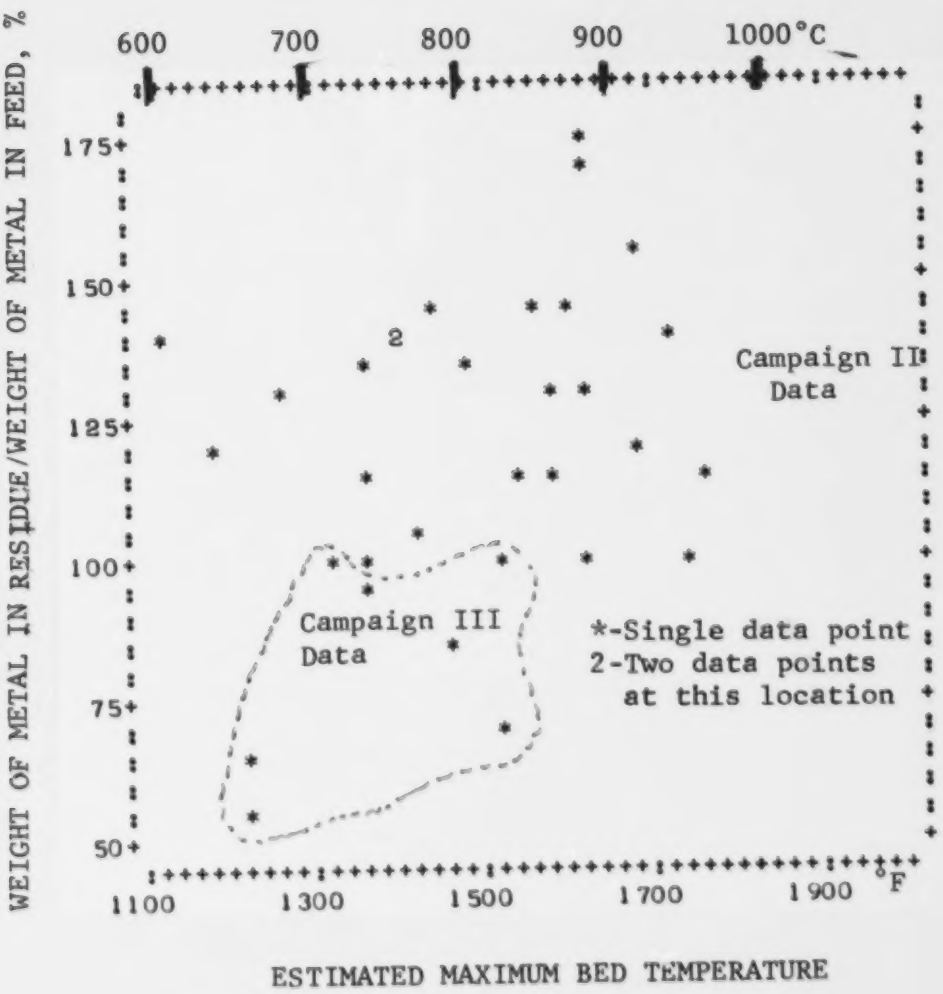

FIGURE 5-12 PERCENT ZN RETAINED

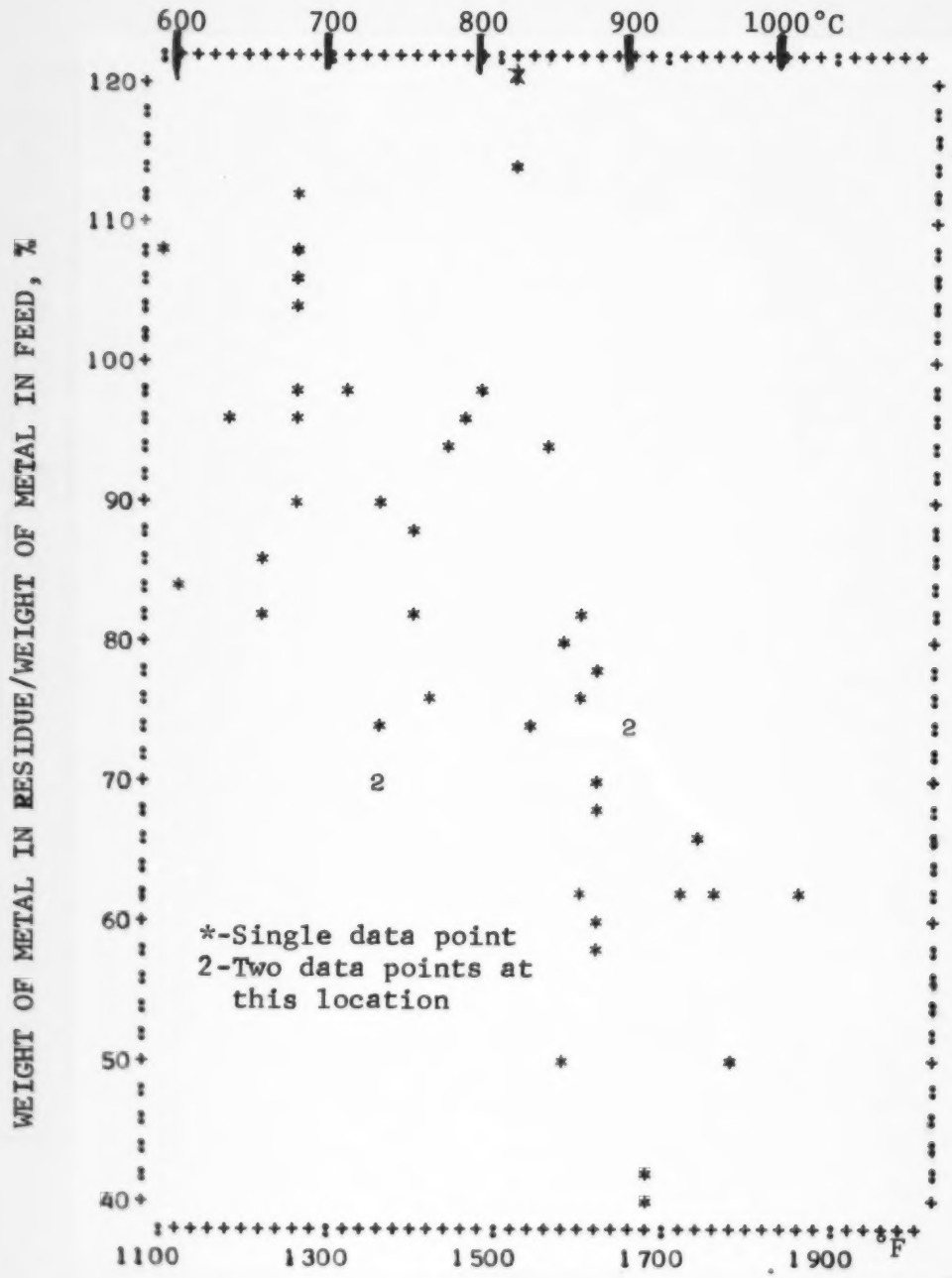

FIGURE 5-13 PERCENT PB RETAINED

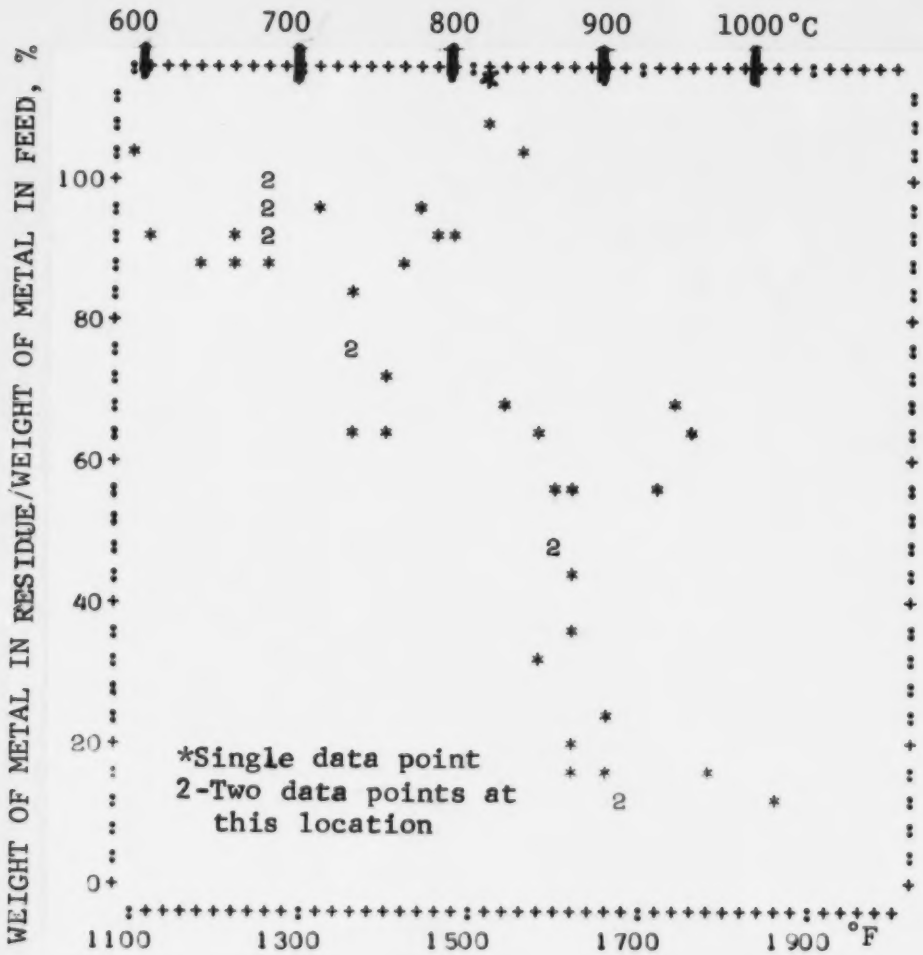

FIGURE 5-14 PERCENT CD RETAINED

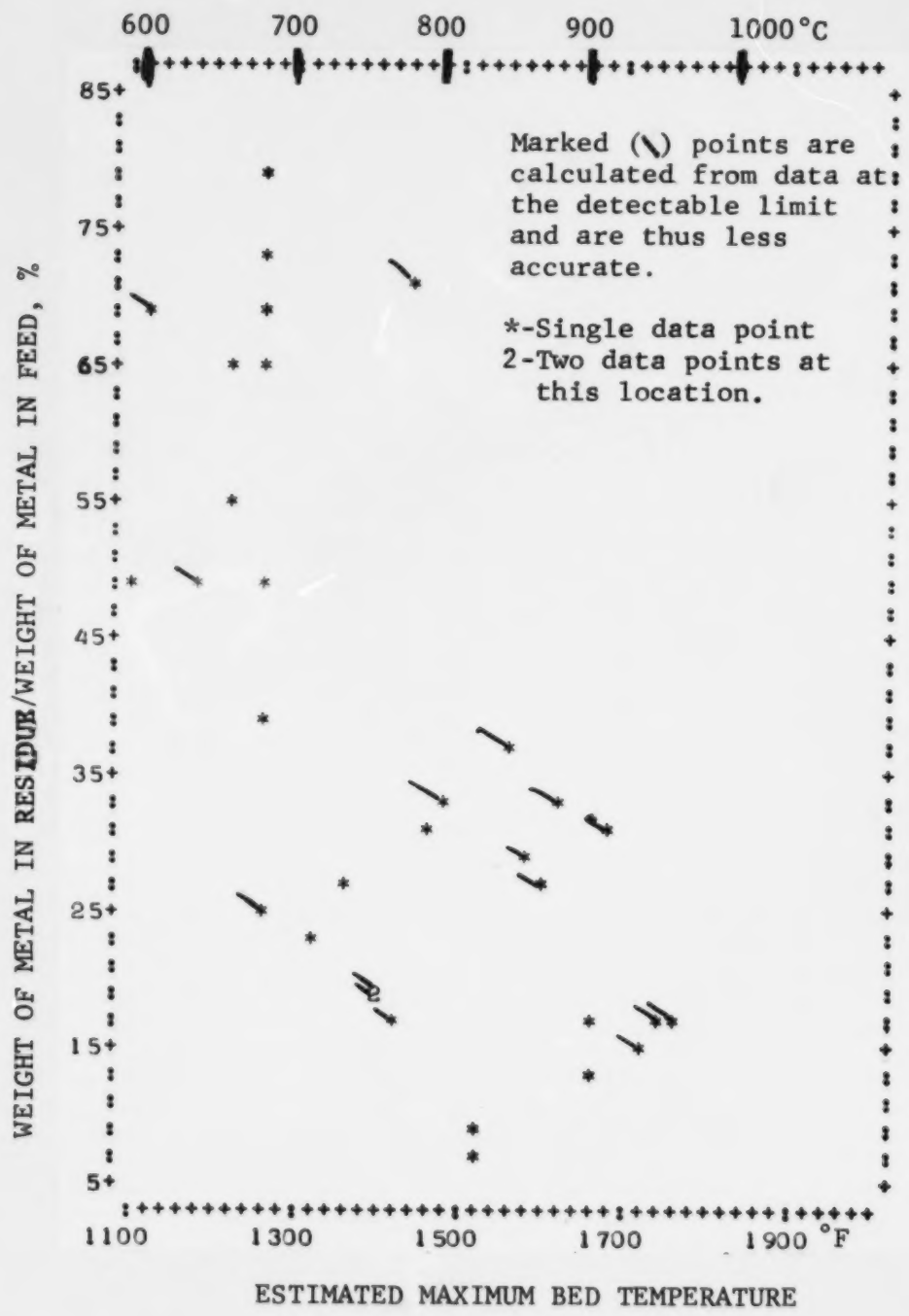

FIGURE 5-15 PERCENT HG RETAINED

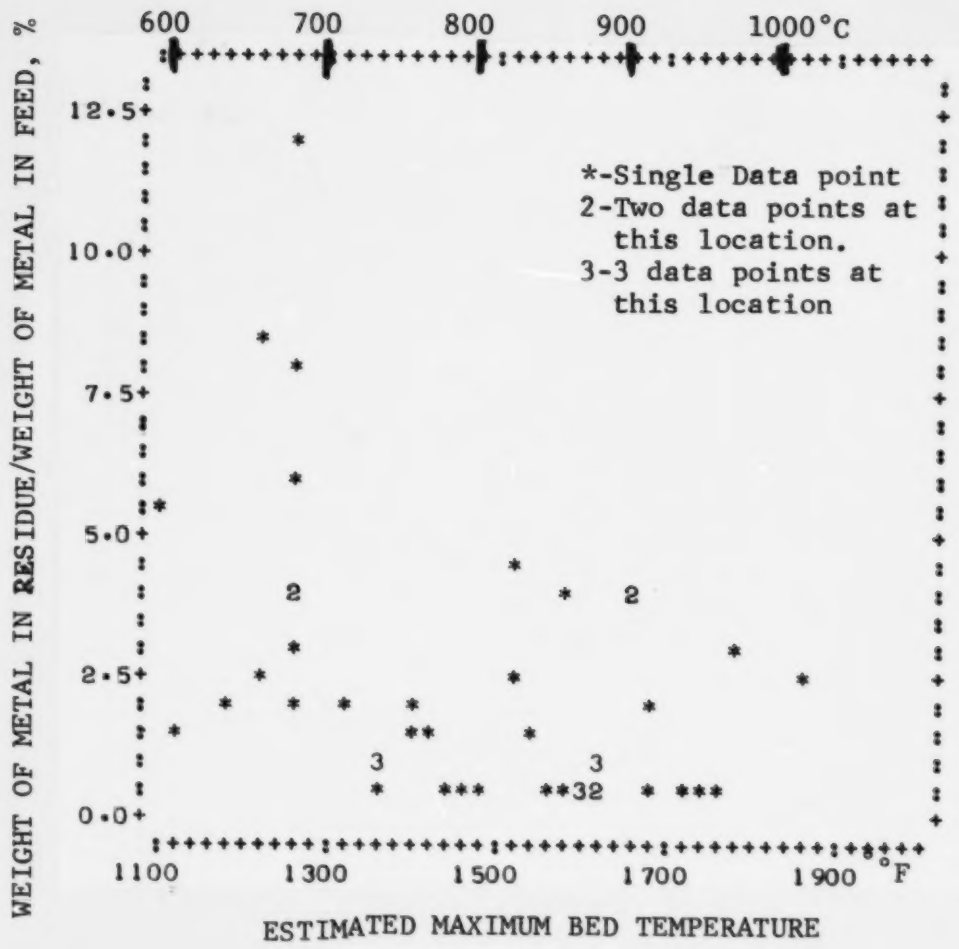

FIGURE 5-16 : HEAVY METALS CONCENTRATION VS. PARTICLE SIZE RANGE AS ANALIZED BY X-RAY FLUORESCENCE (AFTERBURNER INLET, STEADY STATE 3, CAMPAIGN IIA)

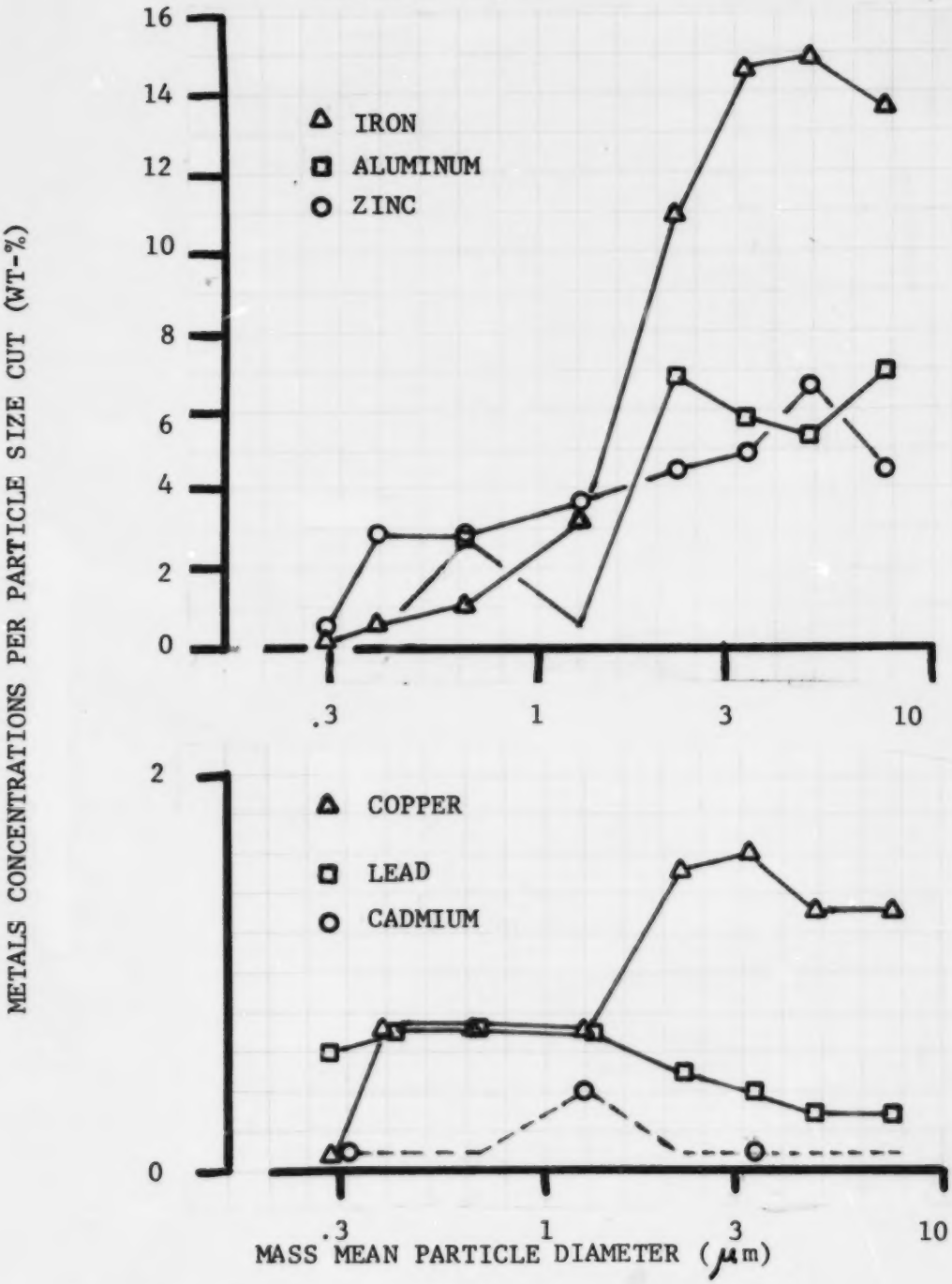

FIGURE 5-17 : DETECTION RATIO FOR HEAVY METALS

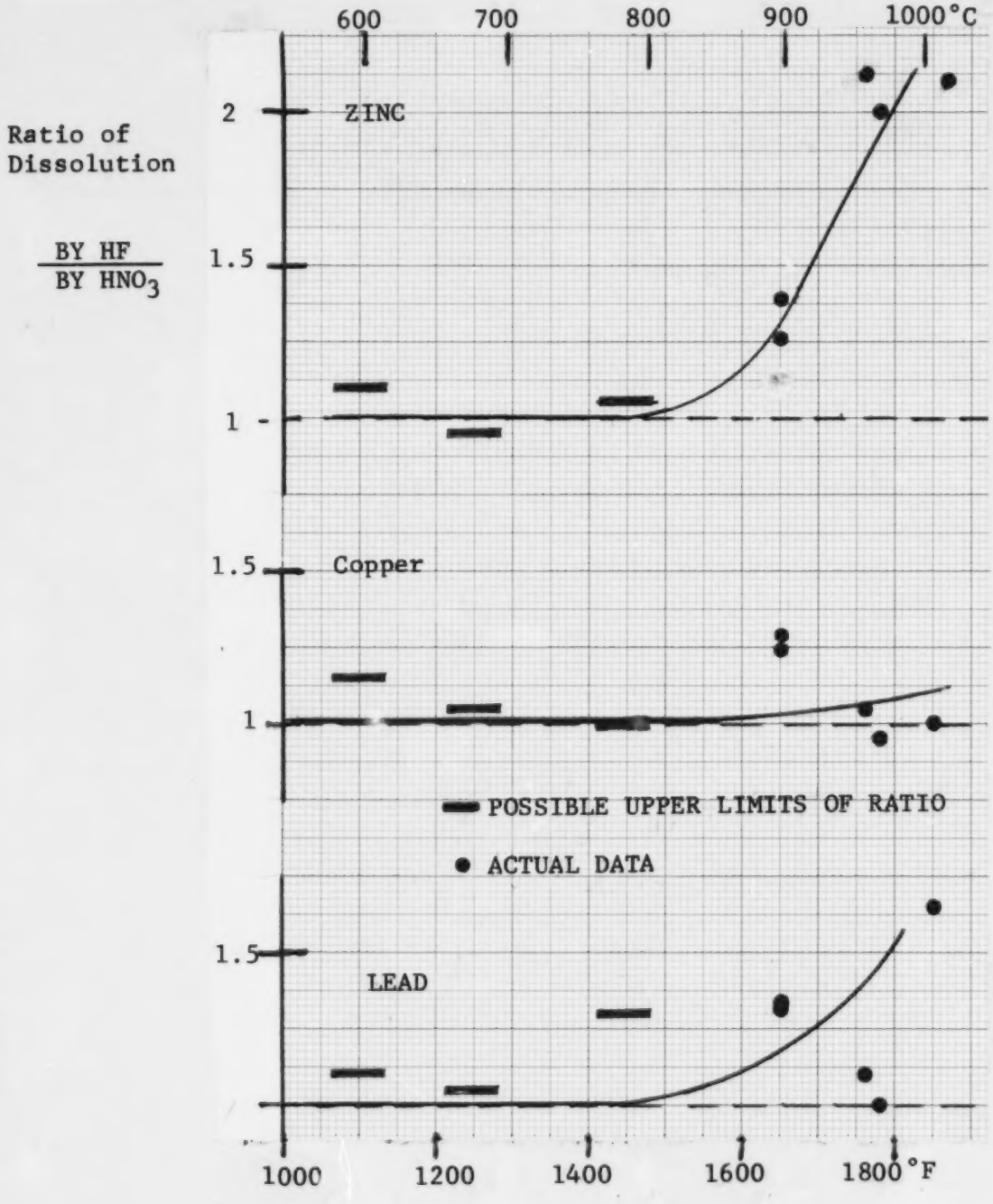

FIGURE 5-17 COND.

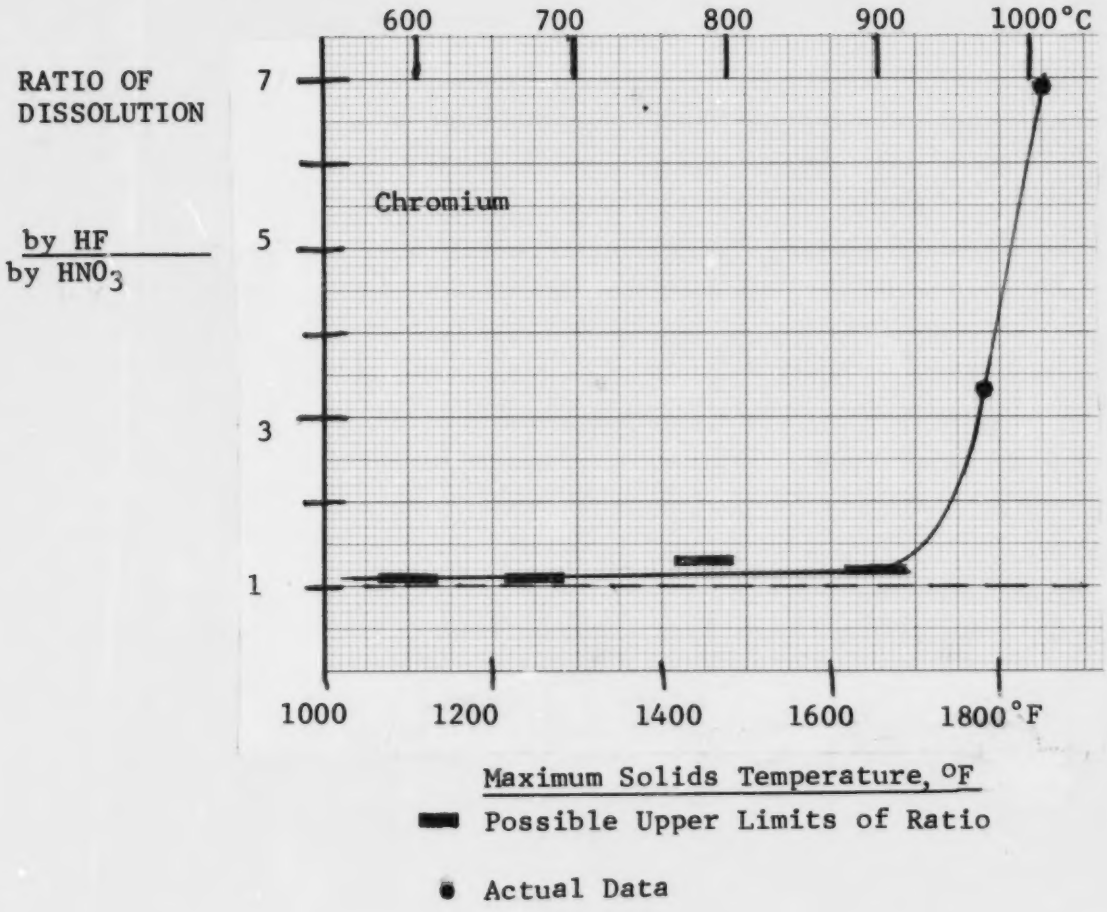

FIGURE 5-18 TEMPERATURE DEPENDENCE OF SUBMICRON SIZED PARTICULATE FORMATION

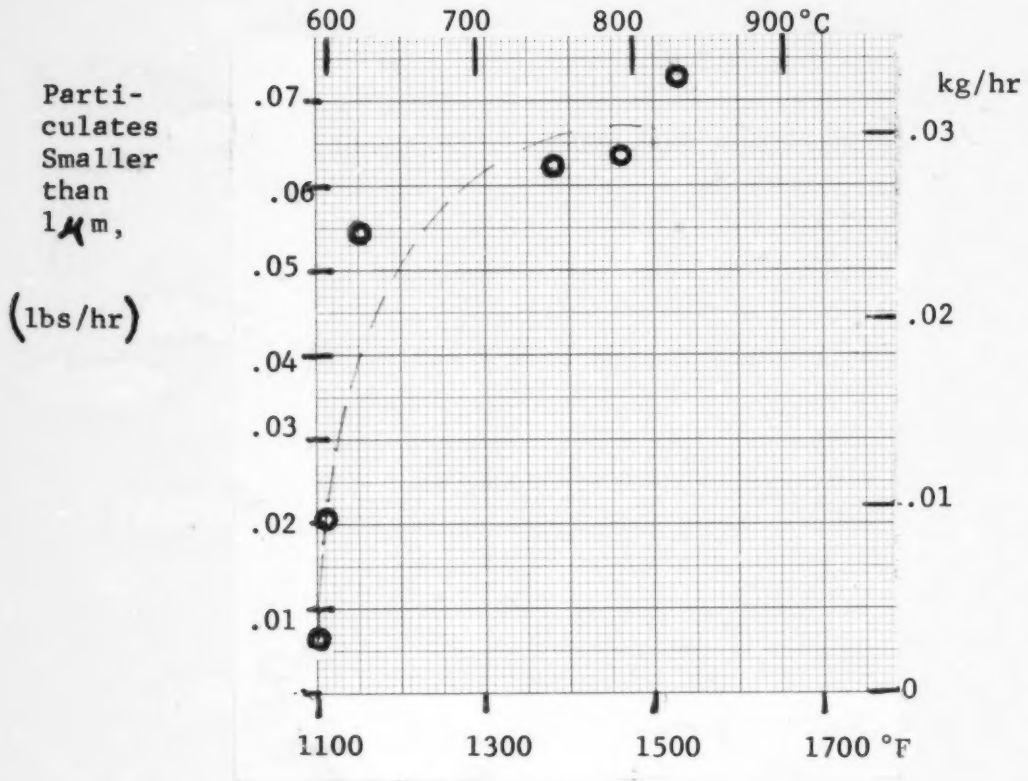

FIGURE 5-19 FINAL VERSION OF SLUDGE CONDITIONING SYSTEM

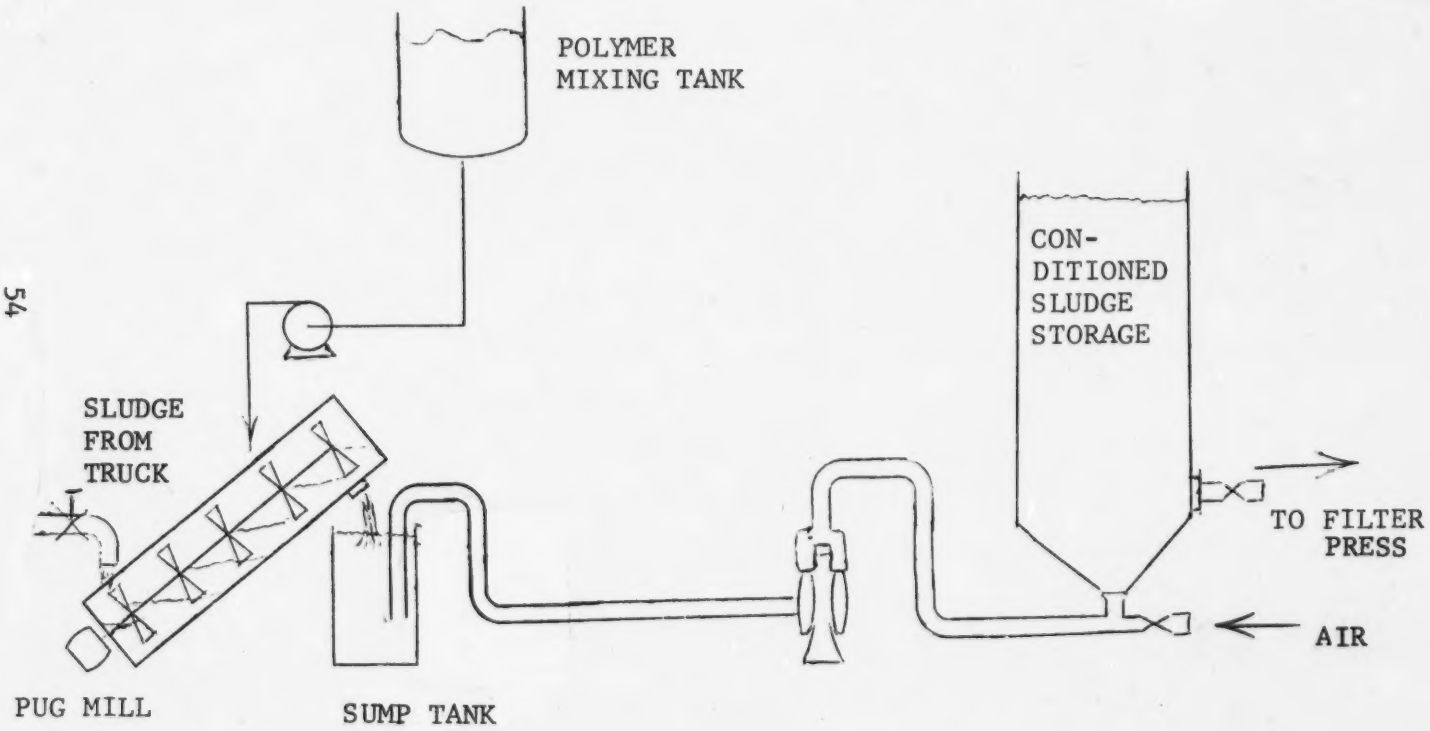

FIGURE 5-20

PILOT FILTER PRESS

(DIAPHRAGM PUMP IN FOREGROUND)

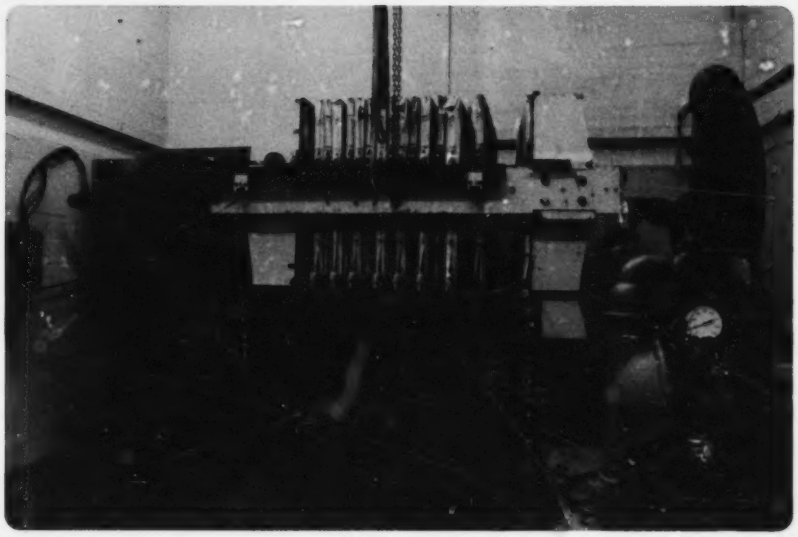

FIGURE 5-21 CONVENTIONAL FILTER PRESS

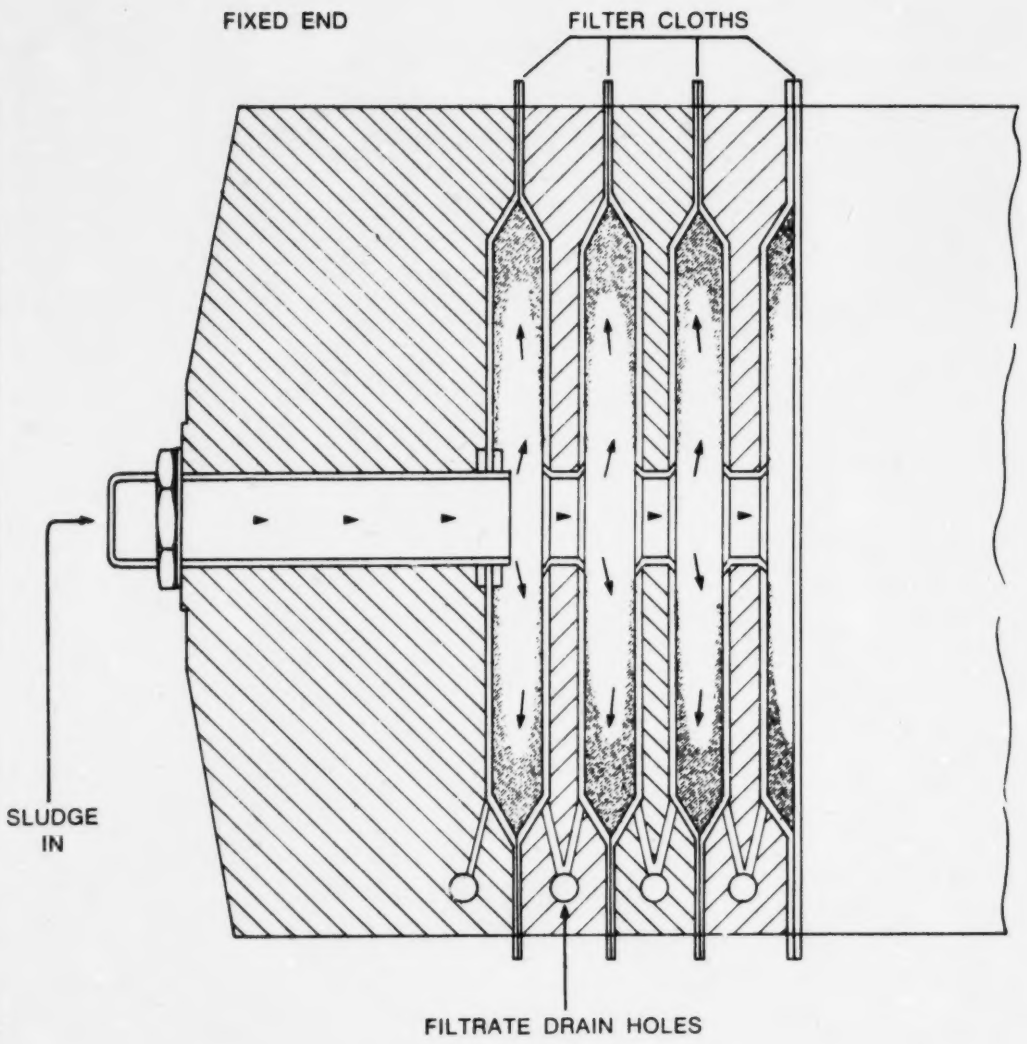

TABLE 5-1

PYROLYSIS FEED RATE AS INFLUENCED BY MOISTURE CONTENT

PYROLYSIS MODE	22% DRY SOLIDS		35% DRY SOLIDS	
	Dry lb/hr ft^2	Wet lb/hr ft^2	Dry lb/hr ft^2	Wet lb/hr ft^2
LTC	2.9	13	4.9	14
HTC	3.3	15	5.6	16
CBA	2.6	12	3.5	10

TABLE 5-2: CARBON GASIFICATION RATES

HEARTH ATMOSPHERE %						GAS TEMP.		%FC AT RATE CHANGE	INITIAL RATE	
N_2	O_2	CO_2	CO	H_2O	H_2	^oF	(^oC)		$\frac{lb}{hr\ Ft^2}$	$\frac{kg}{hr\ m^2}$
54.3	0	5.1	4.0	36.5	-	1823	(995)	6-8	.86	(4.2
63.4	4.4	7.3	~0	25.2	-	1742	(950)	4-7	.67	(3.3)
51.8	0	7.5	3.2	39	1.32	1596	(869)	8-9	.30	(1.5)
72.7	2→4.6	9.5	~0	15.9	-	1608	(876)	5-6	.30	(1.5)
61.7	4	6.5	~0	27.9	-	1588	(864)	6-7	.25	(1.2)
75.1	9.4	6.1	~0	10.0	-	1599	(871)	< 1	.40	(2.0)

TABLE 5-3 SUMMARY OF HEAT CONTENTS AND ENERGY BALANCES

P/I OPERATION	STEADY STATE	% SOLIDS IN FEED	HEATING VALUES (BTU/LB)* FEED SOLIDS	HEATING VALUES (BTU/LB)* PRODUCT	HEAT CONTENTS (BTU/SCF)*# FURNACE OFF GAS	HEAT CONTENTS (BTU/SCF)*# CONTRIBUTION FROM FUEL	HEAT CONTENTS (BTU/SCF)*# NET IN OFF-GAS
P	I .7	31.0	6766	3332	73	55	18.4
P	II A2	38.4	9369	5487	60	0	60
P	II A3	37.5	9039	3795	65	0	65
I	II B1(R)	44.0	9469	1096	42	0	42
P	III .1	32.6	10,451	4163	71	2.6	68
P	III .2	34.4	10,187	2776	81	8.2	73
I	III .5	29.5	9872	433	45	3.6	41
E	III .6	27.9	9730	643	55	2.7	52

P Pyrolysis
I Incineration
E Operation with some excess O_2 on bottom hearths
* Basis liquid H_2O at 60°F (15°C)
# Assumes a gas molecular weight of 26, 1 atmosphere pressure, and 60°F (15°C).

TABLE 5-3 (cond.)

TOTAL ENERGY BALANCE HEAT OUT % HEAT IN	HEATING VALUES ($x10^6$ J/KG)* FEED SOLIDS	PRODUCT	HEAT CONTENTS ($x10^6$ J/M^3)*# FURNACE OFF-GAS	CONTRIBUTION FROM FUEL	NET IN OFF-GAS
105.1	15.7	7.74	2.7	2.0	.69
97.6	21.8	12.8	2.2	0	2.2
102.6	21.0	8.83	2.4	0	2.4
95.4	22.0	2.55	1.6	0	1.6
102.4	24.3	9.68	2.7	.097	2.6
98.7	23.7	6.45	3.0	.31	2.7
77.9	22.9	1.01	1.7	.13	1.6
74.9	22.6	1.49	2.0	.100	1.9

* Basis liquid H_2O at 60°F (15°C)
# Assumes a gas molecular weight of 26, 1 atmosphere pressure, and 60°F (15°C)

TABLE 5-4 HEAVY METAL ACCOUNTINGS IN CAMPAIGN III
STEADY STATES

STEADY STATE:	1		2		4	
	A	B	A	B	A	B
MODE OF OPERATION:	LTC Pyrolysis		1500°F (800°C) Pyrolysis		Incineration	
Cu	58.0	0.04	79.5	.079	100.1	.16
Zn	85.7	0.45	101.7	6.24	114.4	6.57
Cr^{+3}	78.3	0.014	85.7	.033	81.7	.086
Cd	60.7	0.069	7.5	1.81	24.0	7.42
Ni	63.0	0.14	73.2	.24	136.8	1.11
Pb	93.4	0.115	98.3	.304	87.2	.72
Hg	5.7	-	3.0	-	.8	-

STEADY STATE:	5		6		7	
	A	B	A	B	A	B
MODE OF OPERATION:	Incineration		CBA	Pyrolysis*	CBA	Pyrolysis*
Cu	127.5	.39	89.8	.43	77.5	.14
Zn	119.8	.74	87.9	.88	92.9	.329
Cr^{+3}	77.9	.055	80.0	.082	84.3	.33
Cd	28.1	10.4	25.6	28.7	30.4	9.0
Ni	91.7	.49	92.6	4.42	80.6	2.6
Pb	85.3	1.50	81.1	6.88	87.3	.60
Hg	.7	-	1.8	-	.9	-

A % of metal retained in furnace product
B % of metal seen at afterburner stack

*10-30% excess oxygen present

TABLE 5-5 SUMMARY OF PARTICULATE TESTS AT AFTERBURNER STACK

STEADY STATE	DESCRIPTION	TOTAL EMISSIONS LB/DRY TON OF FEED	(KG/MG OF FEED)	MASS MEAN DIAM. UM	1 UM CUTOFF,%
Campaign I					
1	Updraft, excess air	1.5	(.77)	-	-
3	updraft pyrolysis	1.5	(.74)	-	-
7		2.3	(1.2)	.62+	61+
9		0.91	(0.46)#	-	-
Campaign IIA					
1	updraft pyrolysis	-	-	<0.2	67
2		.87	(.43)#	4.0	15
Campaign III					
1	split draft pyrolysis	.77*	(.39)#	0.5	65
2		2.0	(1.0)	<0.2	88
4	updraft incineration	5.6	(2.8)	<0.2	72
5		6.3	(3.1)	5.8	27
7	split draft com- bustion with excess	4.5*	(2.3)	1.7	41
8		3.8	(1.9)	0.96	51

+Distribution microscopically determined

*Tests were not done isokinetically

#Met "New Source" limit of 1.3 lbs particulates/dry ton fed (.65 kg/mg)

TABLE 5-6 SUMMARY OF INITIAL SLUDGE TESTING

IDENT.	DOSAGE (% OF SLUDGE SOLIDS)			CAKE SOLIDS	HIGHER HEAT OF COMBUSTION OF DRY SOLIDS			HEAT AVAILABLE PER LB. OF WATER IN FILTER CAKE	
	$FeCl_3$	$Ca(OH)_2$	Polymer[d]	%	BTU/# ($\times 10^6$ J/kg)			BTU/#water (10^6 J/kg)	
RAHWAY PLANT:									
Raw	3	10	---	27.2	8,880	(20.6)	(a)	3318	7.71
	---	---	0.36 (H844)	36.2	10,398	(24.2)		5900	13.70
Digested	7	25	---	---	No cake				
	---	---	0.47 (H859)	24.3	8.469	(19.7)		2719	6.32
CONEY ISLAND PLANT:									
Raw	3	10	----	---	No cake				
	---	---	0.4 (H844)	40.0	8,950	(20.8)	(b)	5967	13.86
Digested	5	30	----	44.9	4,982	(11.58)		4060	9.43
	---	---	0.72 (P776)	39.9	7,148	(16.61)		4746	11.02
26TH WARD PLANT:									
Raw	8	26.5	---	26.7	---	---		---	---
	---	---	0.2 (P776)	26.8	---	---		---	---
Digested	8	25	---	40.8	4,434	(10.30)		3056	7.10
	---	---	0.65	25.1	6,206	(14.41)		2080	4.83
CEDAR CREEK PLANT:									
Raw	5	15	---	31.9	7,667	(17.81)	(c)	3591	8.34
	---	---	0.35 (P776)	22.5	10,616	(24.67)	(a) (c)	3082	7.16
Digested	5	15	---	---	No cake				

NOTES:

(a) Value calculated from other dosage, same sludge data.
(b) Calculated from ultimate analysis.
(c) Duplication of heating value results from Cedar Creek was only as good as $\pm$ 35%.
(d) Polymers evaluated in these tests include Hercofloc 844 and 859 and Percol 776.

TABLE 5-7 HEAVY METAL AND TOXINS IN FILTRATE AND FILTER CAKE
(in ppm)

	CAMPAIGN I		CAMPAIGN II		CAMPAIGN III	
	CAKE*	FILTRATE	CAKE*	FILTRATE	CAKE*	FILTRATE
Cu	700	.03	280	.15	270	.03
Cr^{+3}	100	<.02	70	<.02	330	.1
Zn	750	.07	400	.02-.7	1500	.1
Cd	3	<.01	2	.01	15	<.01
Hg	3	.0005	2	.0025	2	.0007
Pb	300	0-.02	200	.2	90	.1
As	5	<.1	<2	0-.08	.5	<.01
Ni	-	-	20	.2	80	.4
PP'DDE	.06	Nil	.03	$.026 \times 10^{-3}$	Nil	Nil
Dieldrin	.02	Nil	.03	$.15 \times 10^{-3}$	Nil	Nil
PCB	1.2	Nil	1.0	Nil	Nil	Nil

*Wet basis, 30 to 45% dry solids

TABLE 5-8 OTHER MEASUREMENTS OF FILTRATE (mg/l)

	CAMPAIGN I		CAMPAIGN II		CAMPAIGN III
Conditioner	Polymer	Ferric & Lime	Polymer	Ferric & Lime	Polymer
Phosphate as P	7.2	0.47	79	11.5	79
Total Carbon	1440	200	2200	1650	1450
Total Organic Carbon	330	180	2160	1640	1370
BOD_5	220	160	3610	3450	--
Nitrate and Nitrite as N	. 38	.43	136	.14	.5
NH_3 as N	1060	1030	106	121	197
Total N	1180	1120	144	139	204
PCB's	Nil	---	---	---	Nil
P,P'-DDE	Nil	---	$0.026X10^{-3}$	---	Nil
Dieldrin	Nil	---	$0.15X10^{-3}$	$0.037X10^{-3}$	Nil

TABLE 6-1

Summary of Conversion Cost Estimates (1)

	$ (2)
1. Seal furnace	$25,000
2. Split draft duct	29,000
3. Dampers	11,000
4. Burner modifications	7,500
5. Injection air fan	8,000
6. Injection air piping	24,000
7. Afterburner	68,000
8. Emergency gas outlet stack	23,000
9. Quencher-scrubber	43,000
10. Char cooler	35,000
11. Instrumentation	55,000
12. Wiring	42,000
13. Painting	8,000
14. Contingencies ($\sim$ 5%)	21,000
TOTAL	$400,000

(1) Detailed description in text
(2) All costs include detailed engineering design, installation material and labor and contractor's fees and overheads.

TABLE 6-2

FUEL REQUIRED FOR VARIOUS
METHODS OF THERMAL DISTRIBUTION

% SOLIDS	REQUIRED FUEL, GAL/DRY TON			
	LTC	HTC	CBA	INC
22	80	80	57	100
32	19	19	0	41
39	1	1	0	17
45	0	0	0	3

TABLE 6-3

INCINERATION-DIFFERENTIAL COST/DRY TON
(22' x 10H INCINERATOR)

% Cake Solids	Rate Dry Tons/ Day	Gal Oil/ Dry Ton	Filter (3) Press Investment $mm	Conversion Investment $mm	Investment Related Cost (2)	Fuel Cost (1) $/Dry Ton	Total Cost $/Dry Ton
22	63	100	---	.2	.90	40.00	40.90
32	92	41	2.3	.2	7.84	16.40	24.24
39	122	17	3.0	.2	7.65	6.96	14.61
45	151	3	3.8	.2	7.59	1.24	8.83

(1) No. 2 fuel oil - $0.40 per gallon

(2) Capital amortization taken @ 7% for 20 years, equivalent to 0.0943 rate, i, (from interest tables).

(3) Filter press capital cost taken from Phase I report, Camp, Dresser, & McKee, Table VIII-4, page viii-19.

TABLE 6-4

LTC PYROLYSIS-DIFFERENTIAL COST/DRY TON
(22' x 10H INCINERATOR CONVERTED TO A PYROLYZER)

% Cake Solids	Rate Dry Tons/ Day	Gal. Oil/ Dry Ton	Filter (3) Press Investment $mm	Conversion Investment $mm	Investment Related Cost (2)	Fuel Cost (1) $ Dry Ton	Total Cost $/Dry Ton
22	85	80	--- -	.4	1.35	32.00	33.35
32	123	19	3.10	.4	8.13	7.60	15.73
39	150	1	3.78	.4	7.96	.40	8.36
45	179	0	4.51	.5	7.84	0.	7.84

(1) No. 2 fuel oil - $0.40 per gallon.

(2) Capital amortization taken @ 7% for 20 years, equivalent to 0.0943 rate, i, (from interest tables).

(3) Filter press capital cost taken from Phase I report, Camp, Dresser, & McKee, Table Viii-4, page viii-19.

TABLE 6-5. CALCULATED PAYOUT ON DIFFERENTIAL COST FOR A CONSTANT CAPACITY PYROLYZER

% Dry Solids	Cost Dry Ton, $	$Saved Dry Ton	$Saved Year	Added Investment, $	Payout Years
22	33.35	7.55	165,000	400,000	2.4
32	16.53	24.37	530,000	2,100,000	3.9
39	9.33	31.57	690,000	2,100,000	3.0
45	8.93	31.97	700,000	2,100,000	3.0
50	8.93	31.97	700,000	2,100,000	3.0

NOTE:
1. Size, 22'3" X 10 hearth furnace.
2. Throughput 21,800 dry tons/year
3. Basis, incinerator differential cost shown on Table 6-3 ($40.90/dry ton)
4. Added investment includes $400,000 for conversion to pyrolysis plus $1,700,000 for filter press installation.